Renewable and Sustainable Energy Reviews 27 (2013) 806–852

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainable soy biodiesel

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A R T I C L E I N F O

Article history:
Received 19 March 2013
Received in revised form
5 July 2013
Accepted 14 July 2013
Available online 27 August 2013

Keywords:
Soy biodiesel
Sustainability
Argentina
Brazil
United States
Europe

A B S T R A C T

The sustainability goals for soy biodiesel are to contribute to energy security by providing a domestically sourced fuel, to maintain and enhance the natzural resource base and environmental quality, to produce an economically viable fuel, and to improve the quality of life. Sustainability is more than just greenhouse gas savings. The main aspects of sustainability of soy biodiesel are environmental, economic and social effects of production and use. The intent of this paper is to identify the major sustainability concerns associated with specific resource use and the potential environmental and social consequences of widely deployed and expanded commercial production and use of soy biodiesel and to explore the opportunities for mitigating these concerns. The ecological and socio-economic consequences of large-scale renewable energy action plans for soy biodiesel are critically considered. This paper is based on the performance and prospects of soy biodiesel production on a global basis as emerging from some 30 life-cycle analyses relative to the main production areas (USA, Brazil, Argentina and PR China).

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.07.031

1. Introduction

The production and use of renewable energy are growing in many parts of the world and countries seek to diversify their energy sources in a manner that helps promote economic development, energy security and environmental quality. The components of a complete bioenergy system include feedstock production, conversion technology, and energy allocation. Modern bioenergy can provide multiple benefits but is also associated with risks. If land use is not well planned and enforced, increased deforestation, loss of peatlands and land degradation can occur, which lead to an overall negative impact on climate change.

Biofuels can represent an environmentally friendly replacement of fossil fuels. Biofuels use is expected to rise from 7 Mt in 2005 to 29 Mt in 2030 (OECD/FAO estimate) [1]. The oilcrops sector has been one of the most dynamic parts of world agriculture in recent decades. Globally, the harvested area in oilcrops expanded by 65 Mha between 1990 and 2005. Oilcrop production is relatively land-intensive. Total vegetable oils production is expected to increase from 138 Mt in 2010/2011 to 180 Mt in 2020/2021.

Global soybean production 2010 amounts to 243.9 Mt, with a forecast of 271.4 Mt for 2012/2013 [2]. The market for soy is determined by demand for soy meal. Global soy meal consumption is estimated to rise from 175 Mt in 2010/2011 to 225 Mt by 2020 (with a market share increase from 55% to 57%). Of the main producer areas only South America has sufficient land reserves to expand soy production significantly. Of the foreseen production growth 70% is expected to be covered by South American producers [3]; *cf.* also Table 3. Since the EU Directive on Biofuels (EC, 2003) [4] came into force there has been a growing concern on the origin of biocrop resources [5,6]. In particular, environmentally friendly replacement of fossil fuels can be questioned at large production scales.

Sustainable bioenergy systems are embedded in social, economic, and environmental contexts and depend on support of many stakeholders with different perspectives [7]. Sustainability and environmental issues of vegetable oils are fundamental in assessing the biodiesel market. Sustainability of biofuels is a controversial issue because of many criteria involved, in particular ecological fragility. Low-carbon fuel policies such as the EU-RED, UK-RTFO and Brazilian Low Carbon Agriculture program (ABC) include minimal sustainability criteria to govern the production of (feedstocks for) biofuels. Consequently, it is timely to reconsider the sustainability of various manufacturing routes based on the best agricultural practice and production technology. It is an objective of this paper to gain insight into the sustainability of soy biodiesel in a global energy system. The paper compares the sustainability of soy biodiesel produced in the United States, Brazil and Argentina and PR China (representing 24% of the global biodiesel market; OECD/FAO outlook 2020).

Agricultural production affects environmental and human health. Agricultural demands have enormous impacts on global ecosystems accounting for 40% of land use and 85% of water consumption. Inadequate policies in agriculture result in potentially negative influences on the environment, including deforestation, soil degradation, over-use of water sources, production of GHGs, pollution from agrochemicals, and destruction of natural habitat and biodiversity. Modern agriculture has masked some significant impacts or externalities, with environmental and health problems documented in USA, Argentina, China and elsewhere [8–10]. The societal burden of these impacts calls for a revision of agricultural policy that shifts production towards methods that lessen external impacts. Ultra-intensive agricultural practices need to be abandoned in favour of a model with enough (not maximised) profitability to make it continuously viable.

Energetic use of biomass offers numerous benefits but also ecological drawbacks. Agriculture can negatively affect the environment through over-exploitation of natural resources as inputs or their use as a sink for pollution. Approximately 30–80% of nitrogen applied to farmland escapes to contaminate water systems and the atmosphere [11]. Agricultural production of biomass for bioenergy is also relatively land intensive, and also partly involves higher transport costs than fossil fuels. There are risks connected with pollution and there is the danger of reducing biodiversity if biomass is cultivated in monocultures. If biomass is used for energy purposes, then the ecological advantages must exceed the negative impacts on human life and the natural environment, such as deforestation, reduction of wild biodiversity, soil erosion, water stress and contamination. Other major hindrances to market penetration of biofuels lie in the infrastructure to move feedstock, biofuels, and fuel blends.

Table 1 illustrates that drastic changes in the overall approach of agriculture are needed, more sustainable with socio-economic and environmental objectives. Priority should be given to sustainable agricultural practices, as also stressed by EU-RED [12]. Sustainable production and consumption are vital for the long-term perspective of global industry and trade. It is necessary to guarantee that biofuels deliver tangible GHG savings compared to fossil fuels. To counterbalance the possible negative effects of net emissions of GHGs, land-use changes, conservation of biodiversity, impacts on food supply and socio-economic impacts various measures have been put in place to ensure their sustainability, *cf.* Section 9. Hobbs et al. [13] describe use of productive but more sustainable management practices.

Sustainability concerns exist due to the relatively low level of resource management (soil, water, pesticides). It is necessary to monitor soil deterioration and declining yields due to nutrient depletion, particularly in hillier land and shallower soils. The economic sustainability of commercial agriculture in marginal ecosystems is yet to be proved [14]. Environmental and ecological sustainability are integrally related to social welfare. In the past, in the field of biofuels policy decisions were made with little regard to the social and environmental consequences [15].

Table 2 lists indicators that express environmental performance of the agricultural sector. However, these indicators are far from ideal; *cf.* Section 9.2. The international Environmental Performance Index (EPI) is an aggregated index, with a set of 22

Table 1
Impacts of large-scale intensive transgenic soybean cultivation in Argentina.

Advantages
- Economies of scale
- Short- to medium-term benefits to national economy (GDP, trade balance)
- Ease of production
- Excellent localisation of biodiesel industrial chain – production and distribution
- Economically viable

Disadvantages
Techno-agronomic
- Monoculture
- Devastation of traditional crops and farming life
- Decline in soil fertility (nutrient depletion, 'mining')
- Growth of agrochemical use
- Phytosanitary problems (appearance of glyphosate-tolerant weeds and new pests)
- Destruction of soil microbial life
- Increased incidence of soil pathogens

Environmental
- Landscape transformation
- Land clearance and tropical deforestation
- Ecological impact on marginal areas
- Negative impact on natural wildlife habitats and biodiversity
- Nutrient depletion
- Ecological contamination (ground and aerial applications of pesticides)
- Threat to freshwater ecosystems
- Degradation of soil and groundwater quality
- Erosion and siltation of rivers and wetlands
- Increased risks of genetic pollution
- Adverse GHG implications

Economical
- Economic dependence on soya monoculture
- Overexploitation of natural resources for export
- Marginalisation of cattle and dairy farming
- Displacement of traditional food crops
- Main beneficiaries: multinationals
- Increased costs of herbicides
- Ecological debt

Social
- Violation of human rights (intimidation)
- Expropriation (expulsion of small farmers)
- Destruction of peasant agriculture
- Concentration of land ownership and agricultural production
- Inequitable agricultural growth
- Unequal distribution of benefits to society
- No poverty reduction
- Decreasing rural employment opportunities
- Rural exodus
- Competition between food and non-food uses
- Reduction of food diversity and security
- Health damage to communities (malnutrition; agrochemicals intoxication)
- Loss of cultural diversity

Table 2
Environmental performance indicators of the agricultural sector.

- Management of water for irrigation
- Livestock concentration
- Pesticide monitoring
- Vegetative cover in agricultural landscapes
- Biomass burning in agriculture
- Agricultural subsidies
- Nitrogen loads in water bodies
- Biological health and productivity of agricultural soils
- Wildlife in agricultural lands
- Agricultural crop diversity
- Area of eco-verified production
- Conservation areas on private lands
- Net greenhouse gas emissions from agriculture

After Ref. [16].

environmental performance indicators measuring different aspects of sustainability, which ranks across a range of pollution control and natural resource management challenges. The EPI rankings reveal several environmental sustainability results. The EPI ranking 2012 (lowest value best) is as follows: Brazil 30, USA 49, Argentina 50 and China 116 [17]. It is noticed that little comparative data exists on agricultural sustainability and water quality.

Modern agriculture relies heavily on nutrient inputs. However, such nutrients are used inefficiently and are partly lost to the environment (*e.g.* GHGs and nitrates). In particular, compared to perennial crops, annual cropping inefficiently utilises water and nutrients resulting in degradation of soil and water quality. Intensive agricultural systems are largely responsible for the increase in global reactive nitrogen compounds, which are associated with significant environmental impacts. Agricultural systems worldwide will need to make further improvements in terms of nutrient cycling, nitrogen fixation, soil regeneration, minimisation of harmful non-renewable inputs (notably pesticides), and intensification of resources through better targeting and precision methods [18]. Agricultural sustainability goes for the best genotypes and best agroecological management. Resource-conserving technologies comprise integrated pest management (IPM) and nutrient management, conservation tillage and livestock integration into farming systems [19]. Adherence to Good Agricultural Practices (GAPs), including rotations and resistance management, is a must for both conventional and biotech crops [20,21].

Sustainability issues have become prominent over the last years. Since 2005, soy producers, traders, processors and non-governmental organisations (NGOs) have been setting up responsible soy producing standards, *cf*. Sections 9.4 and 10.1.2. Such sustainability standards are highly needed beside quality and economic standards. As to the soybean oil commodity, it should be considered that the vegetable oil market is dominated by a small selection of multinational agricultural and trade companies, rather than by countries [22].

2. Biodiesel feedstock

The major markets for vegetable oils are food (81%) and industrial use (19%), including biodiesel. World oilseeds production is forecasted to increase from 413 Mt in 2010/2011 to 507 Mt in 2020/2021, mainly in the developing world (notably Brazil, India and China) [23]. Global vegetable oil production will increase by over 30% from 138 Mt to 180 Mt (and from 41.2 Mt to 52.6 Mt for soy oil). Palm oil is the major global edible oil. The main driver for expansion is the demand for edible oils for food. Food use will increase from 113 Mt to 147 Mt and biodiesel from 18.4 Mt to 26.8 Mt [23]. In these prospects, biodiesel production will account for 15% of total oil consumption compared to 10% in the 2008–2010 period. Use of vegetable oils and animal fats for biodiesel production is expected to reach about 50% of the EU's total domestic consumption, as compared to 37% in 2008–2010.

The choice of feedstock for biodiesel depends on availability, predominant climate and infrastructure, domestic transport fuel markets, economics (quality, price and political interventions), processability and ability to meet product specifications. Feedstock procurement and process flexibility have almost become a mandatory requirement for a commercial biodiesel plant to be profitable. Feedstock accounts for up to 80% of biodiesel cost. Obviously, higher quality feedstocks are more costly.

Industrial-scale biodiesel production is primarily of interest to oilseed producing areas, less so for vegetable oil importing countries. The European biodiesel production is largely rapeseed-based since this crop can be cultivated in the prevailing cool and temperate European conditions [24]; other oil-producing crops such as soybean benefit from warmer climates.

Biodiesel feedstocks are regionally highly diversified. Average crop yields show considerable variability depending on genotype, cultivation techniques, environmental conditions, type of soil and input intensity levels. Up to 2008 the EU Common Agricultural Policy (CAP) included compulsory set-aside regulations which allowed for growing of new and traditional crops (rape and sunflower) for non-food industrial end-uses with full hectare premium (EC Directive 1870/95). Because of the high protein content commonly used for animal feed, the protein-oilseed crop soybean had been excluded from such regulations. In the CAP Health Check of December 2008, the set-aside mechanism was abolished. The main objectives of the EU CAP reform are viable food production, sustainable management of natural resources and climate action and balanced territorial development. Biocrops are no longer a declared priority. The Rural Development Policy is being aligned with the Europe 2020 Strategy.

The most important commercial oils for food use in the EU are rapeseed, sunflower, palm (imported) and olive oil. Soybeans are an important feedstock for biodiesel. Growing amounts of soybean oil (as well as soy biodiesel) are being imported. The current breakdown of feedstock for an average European biodiesel plant is approximately 61.9% rapeseed oil (RSO), 12.7% soybean oil (SBO), 10.9% palm oil (PMO), 8.0% used cooking oil (UCO), 3.4% tallow (TLW), 1.9% sunflower oil (SNO) and 1.4% other oils [25,26]. In view of climatic conditions SBO is most attractive for Southern European biodiesel producers. Spain has lately been a major importer of Argentinean soy biodiesel (now halted for political reasons). Larger biodiesel quota in the EU will accelerate vegetable oil demand. EU production of oilseeds does not follow the increase in demand for biodiesel production. In order to meet both industrial and traditional vegetable oil demand, EU imports should rise by 42% in the 2011–2020 period [23]. In many countries intensification of the production of oilseed crops is limited for a variety of reasons.

Some long-term factors appear to be in favour of a potential replacement of rapeseed and sunflower oils as biodiesel feedstocks by soybean and crude palm oil (climate dependent). In Europe, the cost of RSO typically employed in biodiesel production is roughly 25% higher than that of SBO in the US, which does not contribute to its competitive edge. US farmers change from corn to soybeans even if the value of the corn crop per ha is still slightly higher, because soybeans have lower farming costs (less fertiliser, *etc.*). Soy biodiesel has advantages over its competitors, namely lower production costs than canola and greater suitability for use in colder regions than palm biodiesel.

2.1. Soybean oilseeds

Soybean (*Glycine max* [L.] Merrill), an annual crop belonging to the Leguminosae family, is one of the world's most important sources of plant protein and edible oil for both humans and animals. Soybean, a self-pollinated species which grows to a height of 120–180 cm, has considerable ability to naturally defend itself against insects and diseases.

Soybeans are native to Northeast Asia, are sensitive to temperature changes and require four distinct seasons. Soybeans are traditionally grown in temperate and subtropical regions worldwide but are currently also expanding into tropical regions (*e.g.* Brazilian Cerrado). Soybeans are dominant in the United States, Brazil, Argentina, China and India, but are cultivated also elsewhere (Paraguay, Bolivia, Indonesia, Nigeria, Canada), and are regarded as the most appropriate oilcrop for biodiesel production in South Africa [27].

The area cultivated with soybean is still increasing globally from 36 Mha in 1975 to 91 Mha in 2005 and 102.5 Mha in 2010 [28], with expectations of 123.6 Mha in 2020. Most soybean growth in the 2010–2020 period is expected for Argentina (+7.4 Mha) and Brazil (+4.5 Mha), *cf.* Table 3. A forecast for 2050 indicates a total crop area of 169 Mha with a slight contraction in USA, considerable expansion in South America (Brazil: up to 40 Mha; Argentina: 30 Mha; Paraguay: from 2.7 to 8 Mha; Bolivia: from 0.9 to 8 Mha; Uruguay: from 0.8 to 8 Mha) and almost invariable production areas in China (10 Mha) and India (10 Mha). The basic growth scenario stands for business-as-usual: competing crops will be crowded out, pasture lands will be converted, and pressure to convert native biomes will remain [29]. In the future, additional farmland for soybean production will be more limited as land availability declines and yield improvements are needed.

World soybean production has increased from 125 Mt in 1995 to over 264 Mt in 2010/2011, for 81.2% concentrated in USA, Brazil and Argentina (Table 4). Projections are a 2.2% annual increase to 311.1 Mt by 2020 (Table 3) and a 1.8% annual growth from 2020 to 2030 to 371.3 Mt [29]. The highest annual growth rate (4.5%) is foreseen for Argentina. The top 5 producing countries will continue to account for more than 90% of the world soybean supply. Biotech soy 2010/2011 stands at 75% globally, mainly in USA (93%), Brazil (80%) and Argentina (100%). Soybeans and soybean products constitute the largest traded agricultural commodity, outranking wheat. Soy commodity trade is concentrated with a small number of multinationals. About 34% of soybean production is traded internationally: 92.7 Mt in 2010/2011 [30] with a forecast of

Table 3
Forecasts for the world soybean production.

Geographic area	Soybean production (Mt)		Harvested soybean area (Mha)		Soybean yield (t/ha)	
	2010	2020	2010	2020	2010	2020
USA	85.1	92.9	31.3	33.5	2.72	2.77
Brazil	60.0	78.3	22.4	26.9	2.68	2.91
Argentina	52.9	81.9	18.5	25.9	2.86	3.20
China	15.8	16.6	9.0	9.0	1.76	1.84
India	10.7	15.0	9.5	12.3	1.13	1.22
Paraguay	4.1	5.2	2.7	4.0	1.52	1.30
Canada	3.1	3.5	1.3	1.5	2.38	2.33
Rest of Eurasia	6.2	8.1	4.4	5.6	1.41	1.45
Rest of America	4.1	7.4	2.1	3.8	1.95	1.95
Africa	1.6	2.1	1.3	1.5	1.23	1.40
World	243.9	311.1	102.5	123.6	2.38	2.52

After Ref. [29].

Table 4
Production (kt) of soybean, soybean meal and soybean oil (2010/2011).

Producer	Soybean	Soybean meal	Soybean oil
United States	90,606	35,608	8567
Brazil	75,500	27,850	6920
Argentina	49,000	29,311	7181
China	15,100	43,560	9840
India	9800	7660	1715
EU-27	1048	9675	2236
All other	23,126	21,306	4769
Total	264,180	174,970	41,228

After Ref. [30].

97.3 Mt by 2012/2013 [2]. Global import demand for soybean will reach 137 Mt by 2020 [31]. The entire production of China and India is consumed domestically, the other countries are suppliers to the world market. The USA exports 45% (2010/2011), Brazil 40% and Argentina 19%. China is the main global soybean importer (52.3 Mt in 2010/2011 and forecast of 61 Mt in 2012/2013). Soybean meal (SBM) imports are dominated by EU-27, namely 21.7 Mt (2010/2011). With the high percentage of US and Argentinean crops being genetically modified (GM) European soy imports from these countries have declined. EU GMO labelling requirements for animal feed may increase the EU demand for Brazilian GMO-free meal.

The soybean market has historically been driven by the demand for meal, which is not a very storable product, as opposed to oil (making up 35–40% of soybean value). With the advent of biodiesel, this is now moving towards an oil-driven market with prices at top levels. This renders cost-effective production of soy biodiesel very challenging.

Out of the total SBO production in 2008 33 Mt found food use and 4.5 Mt industrial use. Global soy oil production is expected to increase to approximately 52.6 Mt by 2020. The main SBO producers are China, USA, Argentina, Brazil, EU and India (*cf.* Table 4). China is the world's leading producer of soybean oil (largely from imported and domestically crushed soybeans) and also the largest SBO consumer (11.1 Mt, 2010/2011). Global soy oil trade of about 9.3 Mt in 2010/2011 amounted to 22.7% of total oil production with large differences in SBO export of total soy oil production: Argentina 63.5%, Brazil 24.0% and USA 17.1% [30]. EU-27 shows a negative trade balance (−20.0%). Argentina, Brazil and USA accounted for over 80% of the total oil traded. Soybean oil is co-produced with SBM and an increased demand for the one product obviously determines production of the other, affecting other agricultural product systems [32]. In other words, large-volume mandates for biodiesel affect the animal feed market. A drawback of soybean as biodiesel feedstock is its low yield/ha (from 1.8 to 3.6 t/ha) and oil contents (about 18%).

Smallholder soy farming (declining) is generally practised in rotation with annual crops such as rice, corn, tobacco and cotton. Crop rotations help maintain soil moisture and fertility, reduce farm-level demand for fertiliser, and control insects, diseases and weeds. Three main production practices are found for large-scale soy farming:

- Traditional (non-GMO and GMO) soy planting using tillage causes significant erosion and reduction of soil organic matter (SOM).
- No-till planting of conventional (non-GMO) soy leads to lower erosion and organic matter oxidation rates but to difficult weed control and consequent higher herbicide use.
- No-till planting of herbicide-tolerant Roundup Ready® (RR) soy – widely practised – often allows two crops being cultivated annually. Under this cultivation system indiscriminate use of glyphosate for weed control has serious environmental and health impacts.

Like all members of the legume family, soybeans fix atmospheric nitrogen in the form of ammonia if the proper strain of *Rhizobium* bacteria is present in the soil or if the soil is properly inoculated. Consequently, soy can be produced with minimal nitrogen fertilisation; *cf.* 3.7 kg N/ha for soy *versus* 153 kg N/ha for corn [33], making soybeans economically advantageous for biodiesel production. In the past, Brazil and Argentina have been the only countries in the world where soybean was grown without any N fertiliser. Soybean inoculation with rhizobacteria allows increasing biological nitrogen fixation (BNF) and this results in lower fertiliser inputs and increasing yields (from 0.5 to 1 t/ha). Clearly, BNF is the most sustainable and lowest cost source of N. About 50–60% of soybean N demand is met by BNF. Nitrogen fixation alone is usually insufficient for maximum plant growth and grain yield but in some cases there is no response to added N. Application of N fertiliser may work against the BNF efficiency [34]. The yield response of soybean to N fertiliser application depends on the yield potential of the production environment and any abiotic constraints that reduce crop growth. The timing of N application is critical in determining yield response and economic return.

Nitrogen fertiliser management of soybean is complex, as it can utilise both soil N (mainly nitrate) and atmospheric N_2 [35]. To maximise yield and N_2 fixation by legumes, insight into the interactions between inorganic N supply and N_2 fixation, and between inorganic N supply and plant growth throughout crop development is essential. Fig. 1 illustrates the major fluxes of the agricultural nitrogen cycle in soybean cultivation. The N balance (fixed N in aboveground biomass − N in harvested seeds) is only close to neutral (−4 kg N/ha) when also fixed N to belowground biomass is included.

Although soybeans do not generally need nitrogen fertiliser, they contribute to nitrogen emissions indirectly. Soybean cultivation systems produce soybean and nitrogen fertiliser for the next growing season through nitrogen fixation. This leads to nitrogen emissions in the following season when decomposition occurs. While soybeans do not need much nitrogen for growth, they require a significant amount of phosphorus and potassium – more than corn, wheat and rice. Input costs for soybean are lower than for other commodities.

Soy agriculture causes environmental impacts such as contamination of water and soil, GHG emissions and loss of biodiversity. Soy monocropping (instead of rotation with wheat and maize) has negative effects on soil (nutrient depletion) and biodiversity. In recent years there has been increasing focus on how soybean production affects the environment.

With a yield of up to 3.6 t/ha per crop cycle, soybean is the highest yielding source of vegetable protein (up to 50%) globally. Global average soybean yield is reported as 2.38 t/ha in 2010 but yields are highly variable geographically and range from 0.4 t/ha in Tanzania to 1.13 t/ha in India, 1.7 t/ha in China and 2.86 t/ha in Argentina. A global average yield of 2.52 t/ha is forecasted for 2020, with highest yields for Argentina (3.20 t/ha) and Brazil (2.91 t/ha). Irrigation leads to an increase in productivity of soybean cultivation. Higher yields require substantial R&D investments in advanced soybean producing areas and technology transfers to lower-yield areas. In some acid fields (*e.g.* Brazilian Cerrado), farmers apply lime periodically to increase soybean

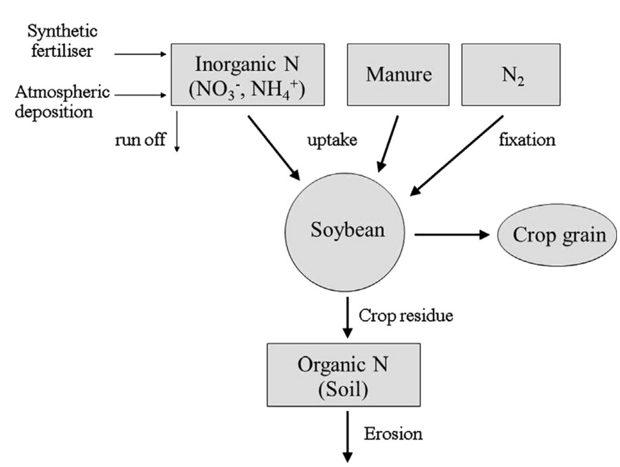


Fig. 1. Major fluxes of the agricultural nitrogen cycle in soybean cultivation.

yield. Higher yields are harvested consistently on farms where conventional soybeans are planted, compared to fields planted to RR soybeans under comparably favourable conditions [36]. Despite the fact that RR varieties produce about 6% lower yields, RR soybeans are preferred because of compatibility with no-till systems, the ease of field operations, lower production costs (by about 10%), and the simplicity of weed management [37].

Soybean yields hard seeds and requires processing in hard crushing facilities, different from the soft crushers for rapeseed and sunflower. Crushing soybeans yields considerably more meal than oil (in approximate ratio of 4.48:1 wt/wt%). Soybean meal and oil serve separate markets. Although SBM is not a by-product of biodiesel production, greater demand for soy biodiesel generates more meal. An important factor in determining the economic viability of biodiesel feedstock is the so-called oil share, *i.e.* the ratio of the economic value of oil to meal. In the last few years, the oil share for soy has increased from about 35% to over 55%, reflecting the increasing demand for biodiesel. However, in many countries, production of biofuel feedstocks is not only driven by demand for biofuels, but also by agricultural subsidies. The oil feedstock accounts for over 80% of total estimated production costs of soy biodiesel [38].

Most of the global soy production (88%) is crushed to yield SBM and SBO, where the latter is just a by-product of the economically more wanted soy meal. Soy is a low-yielding oilseed crop with an oil yield of only about 400 kg oil/ha, that requires vast land areas to produce smaller amounts of biodiesel feedstock than other oilseed crops (*cf.* palm oil, 5550 kg oil/ha). Up to 2005 soy oil ranked as the most important edible oil in the world but has lost market share to palm oil. In 2012 soy attained a global market share of 27.5%. With high global demand for biodiesel and few prospects for significant yield increase (2.8–3.0 t/ha in 2020 for South America), additional cropland is required to accommodate soy production. These reserves, to be found in South America and Sub-Saharan Africa (Angola, Zaire, Sudan), are covered for 30% by forests.

Soybeans are used for a variety of commercial food products, ranging from cooking oil to soy sauce, soy milk and tofu. The demand for soy meal reached 175 Mt in 2010. While only 3% of soybeans are used as animal feed, more than 97% of SBM is used as a high-protein ingredient in concentrated feed for livestock and fish farming [1]. The consumption of soymeal in EU-27 is about 32 Mt (2011/2012) [39]. Industrial soybean-based products comprise paints, detergents, biodiesel and biolubricants [40].

2.1.1. *Biotech soybean*

The global area of biotech crops amounts to 160 Mha (2011), with about equal shares for industrial and developing countries. Biotech megacountries (with more than 10 Mha in 2010) are USA (66.8 Mha), Brazil (25.4 Mha) and Argentina (22.9 Mha) [41]. Growth is highest in developing countries such as Brazil, China, India and Mexico. Biotech crops are the fastest adopted crop technology in the history of modern agriculture. In 2011, 75% of the 100 Mha of soybean planted globally were biotech. Biotech soy is the principal biotech crop, occupying 47% of global biotech area or 75.4 Mha (2011), mainly in USA, Brazil, Argentina, Canada and Paraguay (in descending order), but is grown commercially also in Uruguay, Bolivia, Mexico, Chile, Costa Rica and South Africa [41].

Various soybean lines have been developed for cultivation in the major soybean growing regions in the world. The specific traits incorporated in GM soy crops are herbicide tolerance and insect resistance, not yield. Monsanto's Roundup® brand herbicide kills vegetation by inhibiting the metabolic activity of a particular enzyme, common in plants, that is necessary for the conversion of sugars into amino acids. Herbicides that have glyphosate as the active ingredient are non-selective (*i.e.* kill both weed and crop). Monsanto has also developed Roundup Ready® (RR) seed technology, which involves inserting a chimeric gene into a seed that allows the plant to continue to break down sugars in the presence of glyphosate [42,43]. A gene from the soil bacterium *Agrobacterium tumefaciens* makes the recipient plant tolerant to the broad-spectrum herbicide glyphosate [44]. Crops grown from such seeds are resistant to Roundup® and other glyphosate-based herbicides. RR soybeans were commercially released in the United States in 1996 and introduced in Argentina in the same year (no patent granted). Meanwhile, Argentina has approved four GM soybean lines (*cfr*. Table 15), including Monsanto's new herbicide-tolerant and insect-resistant Intacta RR2 PRO soy (but not the original 40-3-2 event) [45,46]. Approval was delayed in Brazil. In Canada glyphosate-resistant (GR) soybean is grown in the Ontario province.

High-yield, nonherbicide-resistant soy cultivars yield 5% more than non-GR sister lines, which in turn yield 5% more than GR soy. Yield suppression with GR soybean cultivars is related to the gene or its insertion process rather than glyphosate itself [37]. Cultivar choices are therefore to be based on (i) previous weed pressure; (ii) cost of herbicide-resistant cultivars; (iii) cost of pesticides; and (iv) yield. There is little evidence that GM soybean crops are capable of higher productivity [36]. RR technology leads to a per unit production cost reduction of about 10% and to a gross margin gain of 5–10%.

The large GM soy monocultures have developed glyphosate-tolerant weeds as well as pests [47]. As glyphosate is no longer sufficient to control the weeds increasing amounts of a wide spectrum of toxic herbicides (WHO class II), insecticides and fungicides are now needed for pest control. Pest-resistant GM crops can contribute to increased yields and agricultural growth [48]. The longevity of the previous herbicide resource glyphosate and of glyphosate-resistant crop technologies can only be sustained by herbicide rotations and use of non-herbicide weed control tools still to be developed [49].

Soybean breeding has provided site-adapted cultivars for different growth conditions. Embrapa (Empresa Brasileira de Pesquisa Agropecuária; Brazilian Agricultural Research Corporation) has turned soybean into a tropical crop [50] and has created soy varieties that are more tolerant of acid soils than usual and allow short-cycle, no-till, high-yield cultivation in the hot, acidic Brazilian backlands. Embrapa has also developed drought-resistant soybean cultivars.

Being a land-intensive crop as a result of low crop and oil yields conventional soybean agriculture impacts significantly on the environment by inducing land-use change (deforestation, loss of biodiversity, *etc.*). GE crops have delivered record agricultural exports but with considerable environmental, economic and social impacts (Table 1). Although biotech crops have initially reduced the environmental footprint by lower use of pesticides (about 9.1% over the 1996–2010 period) compared to conventional crops [41], this contrasts with the present findings for South American RR soybean cultivation, *cf.* Sections 3.1.1, 10 and 10.1.2. In combination with no-till practice fossil fuels are saved and GHG emissions decreased through no/less ploughing, conserving soil and moisture. The net impact of GM soy on the environment has been judged positive by some [44]. Risks and benefits of genetically modified organisms (GMOs) were discussed by Pretty [10]. The contribution of GM crop production (soybean, maize and cotton) to sustainability is highly dependent on local legal and institutional systems [51].

Major US seed companies (Cargill, Monsanto, Pioneer) are commercialising new soybean varieties that will increase oilseed yields by 9–12% on current acreage, *cf.* also Sections 4 and 5. A yield increase of 10% corresponds to an additional 250 million

bushels of soybeans. Further research is under way to increase the oil yield of soybean by more than 20% [52]. High-oleic acid content transgenic soybeans lines have also been developed. Plant biology plays a critical part in the large-scale development of biodiesel. Long-term supply of soy as a chemical raw material looks positive.

2.2. Soybean oil composition and properties

Protein and oil account for roughly 40% and 20%, respectively, of dry soybeans by weight. Because of differences in genetic varieties, environmental and processing conditions, soybean (SB) and its derived products soybean meal (SBM) and soybean oil (SBO) originating from various countries show up considerable differences in chemical composition (oil, moisture, fatty acid profile) and nutritional characteristics (proteins, amino acids, sugars) [53,54], *cf*. Section 10.1.2. The substitutability of vegetable oils in international trade is limited in particular due to significant differences in their fatty acid profiles.

Soybean oil, primarily composed of five fatty acids: palmitic acid (C16:0, ~10%), stearic acid (C18:0, ~4%), oleic acid (C18:1, ~18%), linoleic acid (C18:2, ~55%) and linolenic acid (C18:3, ~10%), contains a high proportion of polyunsaturated fatty acids (PUFAs, 63.0%) (see Table 5), a characteristic that determines oxidation sensibility. Soy biodiesel offers enhanced biodegradation, reduced toxicity, increased flash point, lower emissions, and increased lubricity. Similar to sunflower oil, conventional SBO with its high iodine value (IV, 121–143 g I_2/hg) does not comply with the EN 14214 biodiesel standard. The problem of low resistance to oxidation and limited shelf-life can be overcome by chemical modification (notably partial hydrogenation and epoxidation) [55], additivation, interesterification with palm oil, blending (*e.g.* with rapeseed or jojoba oil) [56,57], or genetic modification with reduction in C18:3 content [58,59]. Interesterification greatly increases processing costs. Blending is most common [56,60,61]. Also the SBO pour point (PP) problem can be solved by blending with other fluids, or by additivation.

There are several thousand sub-species of soybean. Prior soybean oils often lacked important food quality properties (oxidation stability, saturated fat content, flavour) or biodiesel properties (NO_X emissions, cold flow). The composition of soybean oil can be modified to improve the usefulness of soybeans for food and fuel applications. Seed companies have used molecular marker, traditional breeding and transgenic technologies to incorporate modified oil traits into high-yielding germplasm. Benefits sought by the biodiesel industry are improved oxidative stability and cold-flow properties (for northern climates). This imposes a compromise between PUFA content (for oxidative stability) and SFA content (for cold-flow properties) [62].

Duffield et al. [63] have proposed designed specialty oil modifications by genetic engineering (GE) methodologies directed at including a high-oleic (HO) profile with reduced PUFAs and SFAs for increased oxidative stability under most environmental conditions. Mutational breeding has been successful in generating soybean germplasm with elevated C18:0 content (>20%) [64]; also GE approaches have been successful in increasing the stearic acid content in soybean [65]. High-oleic and high-oleic, low-palmitic oils are substantially more oxidatively stable than commodity soybean oils [66]. This increased stability results in substantially reduced NO_X engine emissions from HO oils when compared with conventional soy biodiesel. Designing a soybean oil with 10–20% ricinoleic acid (C18:1-OH) coupled with 70–80% oleic acid is another desirable target for enhanced biodiesel performance in terms of oxidative stability and lubricity [62].

As a result of intensive quality breeding, the fatty acid profile of soybean oil is now remarkably variable [67]. Table 5 lists some SBO mutants. Conventional soybean oil typically contains about 16–20 wt% SFAs. Low-saturate oils contain between 3.6 and 8 wt% saturated fatty acids. A zero-saturate oil composition contains less than 3.6 wt% SFAs. Methods for producing such altered seed compositions have been outlined [68]. Low-linolenic (LL) varieties (1.5–2.3% C18.3, IV 120 g I_2/hg) – mainly for food applications – improve the oxidative stability but only slightly [69]. For that purpose better alternatives are oil blends, use of antioxidants or high-oleic (HO) oils. High-oleic soybean oils (HOSBOs) are more oxidatively stable than LL oils.

The development of soybean cultivars with oil enriched in oleic acid, such as mid-oleic (43.7% C18:1, IV 107 g I_2/hg) and high-oleic (81.3% C18:1, IV 90 g I_2/hg), is an important breeding objective of the crop. These oils exhibit a higher degree of oxidative stability than oils low in oleic acid. While conventional soybeans contain only approximately 20% C18:1, (more expensive) GE soybean seeds reach 85% of oleic acid [70,71]. HOSBO, which is significantly more saturated than SBO (SFA/MUFA values of 9.5/81.5% and 16.0/21.0%, respectively), shows considerable improvement in thermal and oxidative stability over SBO. The derived oils – mainly for the food consumer market – are about 30 times more oxidatively stable than conventional soybean oil.

A soybean oil that is broadly beneficial to major users in the food *and* industrial markets is not readily available. Pricing and supply issues have prevented HOSBO from becoming a feedstock source for biodiesel. An optimised SBO composition for both food and fuel use has been hypothesised to contain about 24 wt% PUFA [72]. A target soybean oil composition (C16:0, 2.1%; C18:0, 1.0%; C18:1, 71.3%; C18:2, 21.4%; C18:3, 2.2%; other 2.0 wt%) is characterised by CP, PP and CFPP (cold-filter plugging point) values of −18 °C, −21 °C and −21 °C, respectively, which is comparable to or better than the corresponding values for petroleum diesel. The derived CN value was reported as 55.4. Calculated IV (according to DIN EN 14214 Annex B) of 103.1 g I_2/hg is within the EN 14214 limit for biodiesel.

Clearly, even an abundant oil such as soybean oil is not an ideal feedstock for biodiesel in view of its inherent characteristics that

Table 5
Soybean oil mutants according to their fatty acid composition (wt%), indicated by typical average, minimum and maximum values.

Mutant	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3
High-oleic (HO)[a]	6.6	0.0	3.6	84.9	0.6	1.9
Mid-oleic (MO)	4.3–11.1	0.0	3.5–5.0	43.7–55.0	24.0–35.5	<3.1
Low-linolenic (LL)[b]	10.5	0.0	4.6	23.2	59.6	2.0
Low-palmitic[b]	3.7	0.0	3.7	24.1	58.9	8.9
High-palmitic[b]	17.3	0.0	2.9	16.8	54.5	8.3
High-stearic[b]	8.4	0.0	28.1	19.8	35.5	6.6
Conventional	7.0–12.7	0.1–1.0	1.4–5.9	11.5–27.2	51.5–63.1	2.9–12.1

[a] Gene technology.
[b] Mutagenis.

impact cloud point and cold-filter plugging point. The industry needs an emerging, less costly, feedstock with better CP and CFPP characteristics.

3. Agricultural technology

The main objectives of sustainable agriculture are C production (crop yields) and conservation (crop residue management, tillage). Crop yields depend on certain combinations of crop, previous crop, and tillage. Soybean after no-till corn can suffer a 6% yield drag, and soybeans after two years of corn receive a 4% boost [73]. Biomass harvesting decreases the carbon content in soil. The conservation of original conditions (water and nutrient level, soil organic carbon, pore distribution and aggregation) in an agricultural soil, that permit development of sustainable production systems, can be achieved with annual row crop-pasture rotations or with no-till row cropping systems. Reduced tillage systems have been practised since the 1930s that use less fossil fuel, reduce runoff and erosion of soils and reverse the loss of soil organic matter (SOM). No-till (NT) is a sustainable technology [74].

Soybean is mostly produced with modern highly mechanised industrial agricultural systems, based on use of seed varieties, chemical fertilisers, agrochemicals, fossil energy and industrial supplies. This intensive agricultural system leads to various environmental and social problems, including a decrease in soil fertility, intoxication of man and animals, expulsion of small farmers from their land, contamination of water and soil, erosion or siltation of rivers, global warming and a decrease in biodiversity (*cf*. Table 1).

Fuel crop agriculture should be promoted in areas where rainfall can supply the majority of water requirements such as to avoid the need for irrigation. It should be determined if irrigation systems in soybean cultivation are a sustainable practice. The true value of water resources should be reflected in the price of biodiesel [75]. Degradation of water quality represents a major obstacle to sustainable biodiesel production.

3.1. Management techniques

Tillage is an important determinant of environmental quality in cropped land, and because its impacts on yields, is linked to the choice of rotation [76]. Under traditional tillage, rotations with pastures are required to restore soil structure and fertility after several years of cropping. Conservation tillage (CT) was borne out as an agricultural practice after the American dust bowl of the 1930s. It uses some of the principles of conservation agriculture (CA) but with soil disturbance, and is regarded as one of the most effective practices for reducing soil CO_2 emission to the atmosphere. No-tillage (NT) or zero-tillage is an agronomic conservation system in which the crop is sown over the stubble of the former crop and the soil is left undisturbed from prior harvest to no-till planting except for nutrient injection. Table 6 illustrates the main characteristics of NT technology, whereas Table 7 compares CT and NT soybean operations. No-till monoculture is fundamentally the one which requires less labour [77]. However, monocropping also fosters growth and spread of pathogens and increases the dangers of land deterioration and environmental destruction. No-tillage requires specialised planting machinery. Correctly utilised, no-tillage reduces emissions and compaction, and conserves soil resources (water and carbon). Compaction reduces plant growth and yields by affecting water infiltration, aeration, and plant diseases.

Under no-tillage, it is necessary to rotate soybeans, which leave little stubble, with crops such as wheat and corn that contribute a good quantity of stubble and because their root systems contribute to maintain soil structure. Rotation of different crops with different rooting patterns combined with minimal soil disturbance in no-till systems promotes water infiltration to greater depths and increases microbial diversity [78]. No-till and leaving more crop residue cover on the soil surface are effective in reducing CO_2 emissions and thus improving soil C sequestration in a corn-soybean rotation [79]. CO_2 emission is 24% less with no-tillage with residue than without residue covers. Additional benefits are less soil erosion and higher production profitability.

Table 6
Main characteristics of no-tillage technology.

Advantages
- Low ecological footprint
- Reduced production costs
- Better timing of crop harvests
- Conservation of soil resources
- Expanded crop frontier
- Enhanced crop productivity
- Reduced soil deterioration
- Limited soil erosion
- Reduced carbon (GHG) emissions
- Allowance for monocropping

Disadvantages
- Need for specialised planting machines
- Near-total reliance on herbicides

Table 7
Conservation tillage (CT) and no-till (NT) soybean operations.

CT: plow, disk (two times), seedbed preparation, fertiliser application, grain drill planting, pesticide application, soybean harvest
NT: fertiliser application, NT planting, pesticide application (two times), soybean harvest, soybean stubble mowing

After Ref. [80].

No-till farming has a lower ecological footprint than traditional cultivation techniques and allows better timing of crop harvest and pasture grazing [81]. The NT system reduces the energy input into soybean production by 18% when compared to ploughing and disking. No-tillage practices require only 35 L of diesel per hectare as compared to 60 L/ha of conventional tillage (or 42% savings) [82]. In the 1990–1995 period NT systems and soil management for sustainable crop production has increasingly become recognised as a superior alternative to conventional tillage [83].

No-tillage makes soybean cultivation much less sensitive to soil and slope conditions and has allowed planting in areas poorly suited to conventional crop production methods (*e.g.* areas with lower rainfall), contributing to the expansion of the crop frontier (as in Argentina). No-tillage has permitted conversion of some land from crop-pasture rotations to permanent agriculture. No-tillage agriculture is now being adopted throughout the world on more than 100 Mha. Both in USA and Argentina a higher percentage of no-till acres is planted to RR soy varieties than acres grown under conventional tillage and planting systems. South America has the highest adoption rates for NT and permanent soil cover.

No-till management impacts on crop productivity. Water storage conditions are better at the surface of no-till soils. Factors that affect soil organic matter (SOM) content are soil texture, content of fine mineral particles (clay, sill), tillage practice, crop-pasture cycles and mixing with harvest residues [83]. SOM degradation is associated mostly with annual row crop production systems using tillage. Conventional tillage causes SOM losses. No-till cropping improves soybean nodulation from inoculants, minimises SOM losses and maintains or even increases soil C and N stocks [84]. BNF is significantly favoured in no-till systems.

Increasing no-till soybean productivity causes microbial diversity to increase [83].

Crop productivity can be reduced with adoption of no-till, particularly in cooler and/or wetter climatic conditions, but can also increase, depending on the environmental conditions [85]. Reduced N availability under NT management has been suggested as a cause of lower yields relative to full tillage [86].

Average crop yields with use of no-till systems in the Argentinean Pampas are similar to those observed with other tillage systems. No-till adoption in the subhumid and semiarid Pampas are related to soil water conservation that allows adequate planting dates for maximal yields. No-tillage has also greatly facilitated the planting of soybeans immediately following the wheat harvest, resulting in two crops per year.

No-till may limit soil erosion, but it is not the best way of plant protection. The role of tillage on diseases is unclear [78]. Although it would appear that NT results in a better balance of microbes and other organisms and a healthier soil, direct drilling encourages diseases because spores of pathogenic fungi persist in the roots and stems that are left on the soil until the following year. Consequently, more fungicides and pesticides are needed. No-till planting systems near-totally rely on herbicides for weed control. Since the introduction of RR/NT new disease problems have arisen such as Asian rust. For no-tillage seeding in conservation agriculture, see also refs. [81,87].

Conservation agriculture, defined as minimal soil disturbance (no-till) and permanent soil cover (mulch) combined with crop rotations, has been proposed as a more sustainable agricultural cultivation system for the future [13]. CA is an improvement on conservation tillage, where NT, mulch and rotations significantly improve soil properties and other biotic factors. NT plus mulch reduces surface soil crusting, increases water infiltration, reduces run-off and gives higher yield than tilled soils [88]. A cover crop and the resulting mulch or previous crop residues help reduce weed infestation through competition and not allowing weed seeds the light often needed for germination. Mulch helps with recycling of nutrients [13]. Conservation agriculture without tillage has been practised for several decades and has spread widely over 106 Mha of arable and permanent crops [89]. If properly managed, CA has both agricultural and environmental benefits and promotes soil health and productive capacity. CA can make a major contribution to sustainable production intensification. While CA and NT systems create benefits for soil health and reduced off-site pollution they both require increased use of herbicides for weed control [19].

3.1.1. *Crop protection*

Crop protection is an important part of crop production. Much of the global farmland is using crop protection chemicals. In soybean production weeds are the predominant pest group. Almost 37% of attainable production is endangered by destruction or weed competition worldwide compared to 11%, 1%, and 11% by fungal and bacterial pathogens, viruses and animal pests, respectively. Some key pests (*Phakopsora* spp., nematodes) are regionally restricted [90]. The overall loss potential is especially high in crops grown under high productivity conditions (such as large-scale monocultures or with heavy fertiliser applications) as well as in areas where climatic conditions favour the damaging function of pests. In the (sub)tropics the yield potential of adapted crops is often low due to low-input farming systems, whereas the loss potential of pests is high due to climatic conditions promoting the development of pests and continuous cropping practices. Despite actual control measures pests reduced worldwide soybean production by almost 28% (1996–1998). This high loss rate is due to the large-scale production of soybeans in the Americas where the land area available allows production without high expenditures on pest control. Oerke et al. [90] have compared the site-specific loss potential of pests in a no-control scenario with actual loss rates, *i.e*. the losses occurring despite crop protection measures as a parameter to quantify the efficacy of control (50–53% for soybean). Loss potential of pests for soybean is estimated at 37%, actual losses at 28%. Weeds carry the highest loss potential. Worldwide efficacy in weed control (68%) relies heavily on pesticides.

Pesticides play a vital role in food production and can save land. However, in many cases, higher pesticide use in order to produce extra yield is economically not justified because environmental factors other than pests, especially the availability of water, are yield limiting. Pesticides are a significant source of pollution in the environment, affecting both human and ecosystem health. Many pesticides are persistent organic pollutants, endocrine disruptors, or carcinogens. In North America, herbicides are by large the most important pesticides. The most widely used herbicide glyphosate (Monsanto) and highly hazardous insecticide imidacloprid (Bayer) are both systemic (preventive). Both Argentina and Brazil make use of the PAN Highly Hazardous Pesticide (HHP) imazethapyr, no longer used on the European market [91]. Other typical insecticides used, such as the pyrethroids cypermethrin and chlorpyrifos (all PAN HHP), are highly toxic to aquatic environments.

The method of cultivating GM soy in large-scale monoculture increases the need to use agrochemicals. The extensive use of broad-spectrum herbicides with glyphosate, fungicides and insecticides in the non-tillage RR soybean system may impact the health of farm workers and can have severe effects on biodiversity and aquatic environments, such as rivers and lakes, in the large areas where soybeans are the only crop [92,93]. Impact on biodiversity extends to areas beyond those planted with soybeans.

Glyphosate [*N* (phosphonomethyl) glycine] is the world's most efficacious and environmentally benign non-selective herbicide used for broad-spectrum weed killing; the product is considerably cheaper than most other herbicides [94]. Glyphosate essentially has no residual activity and is rapidly decomposed to organic components by microorganisms in the soil. Its toxicity is very low (WHO toxicity class IV) [42]. Glyphosate is the active ingredient in Monsanto's Roundup® herbicides [92]. Roundup® is a combination of glyphosate with other chemicals, including a polyoxyethyleneamine surfactant that enhances the spreading of the spray droplets on the leaves of plants. Roundup® is more toxic than its active ingredient. Adoption of RR soybeans has favoured almost complete abandonment of more hazardous herbicides (tox classes I to III) used in soybeans. Despite being much less toxic than other herbicides, there is evidence of toxic effects of glyphosate on humans and on the environment, and indirect environmental damage and resistance in some target weed species [95]. The pesticide is considered a health concern by inhalation during spraying and therefore requires worldwide health warnings. Its use should be reduced to a minimum as a matter of precaution. The opposite occurs. The major business for Monsanto is not so much the GM seed itself but selling the associated glyphosate pesticide in ever increasing quantities; most recently, low-cost glyphosate has become available from China.

Overspraying is bad for crops and the environment, besides being anti-economical. Intensive use of agrochemicals and illegal pesticide spraying are a problem with undesirable health consequences in Argentina. In the 2009/2010 season more than 200 ML glyphosate were applied in all the Argentina soybean sown area (*cfr*. 13 ML in 1996) [96]. Whereas the Argentine soybean area has increased 2.92x between 1996 and 2010 and its production 4.51x, glyphosate use increased 15.4x in the same period. The way farmers use agrochemicals needs revision. Stewardship and training programmes as well as online reporting of

pest and disease problems will allow farmers to spray at exactly the right time, and use less. Tighter laws and enforcement are needed. Pesticide formulation technology also needs further improvement. Clever formulation can make a real impact on a pesticide's effectiveness and the amount that needs to be sprayed onto crops. Localised application of pesticides around the seed (precision farming) makes agriculture more sustainable.

Glyphosate applied alone is rapidly losing its efficacy and growers must use more diverse weed management programmes to maintain its effectiveness. Maintenance of diversity in weed management systems is crucial for glyphosate to be sustainable [49,97]. This will involve herbicide rotations, sequences, combinations of robust rates of different modes of action and non-herbicide weed control tools. Such diversity must be introduced in the transgenic glyphosate-resistant crops (GRCs) areas of the USA, Argentina and Brazil if glyphosate is to be sustained. GRCs have enabled producers to reduce tillage, with concomitant environmental benefits, but this results in reduced diversity on the weed management techniques practised. Multiple-herbicide-resistant crops allow more weed management options [98].

The strong selection pressure exerted by the widespread use of glyphosate has led to the emergence of resistance in some weeds [49,99,100]. In regions of the USA, Argentina and Brazil where GRCs dominate, glyphosate-resistant weed species have developed [101]. Despite the fact that total glyphosate use on soybeans increased 50-fold from 1996/1997 to 2003/2004 in Argentina weed resistance to glyphosate has become more widespread [93]. US farmers are relying more heavily on other herbicides in managing weeds on their RR acres. Moreover, Asian soy rust disease has caused substantial yield losses in Brazil (-3.4 MMT in 2003), requiring fungicide application. White mould (*Sclerotinia* stem rot) is another soybean disease. In rotation of soybean with other crops the diversity of herbicides used increases, which decreases the risk for weed resistance.

Glufosinate crop resistance (Liberty Link®; Bayer CropScience) is the most common commercial non-GR trait. Glufosinate controls a wide spectrum of weeds and is a (highly hazardous) alternative to glyphosate. There are no weeds resistant to glufosinate.

3.1.2. *Land-use change practices*

Mechanised soy cultivation is a highly intensive form of land use. As more soybean biodiesel production is integrated into the agricultural sector it will be important to adopt land-use practices that efficiently utilise nutrients and minimise erosion, such as rotation cropping.

Since the expansion of biofuel production requires land to grow the biomass feedstocks, land-use change (LUC) is usually inevitable. However, land-use change is not an inherent biodiesel property. Two types of LUC may be envisaged: intensification (*e.g.* increased corn and decreased soybean on currently cropped land) or extensification (using land currently out of agricultural production such as US Conservation Reserve Program or CRP land). Returning CRP land to agricultural production has disproportionally high per hectare effects on soil erosion and nutrient losses. Section 4 illustrates the effects of changes in land use (alternative rotation and tillage schemes) in the US Corn Belt [102]. Environmental concerns arise from soybean cultivation expanding mainly at the expense of natural vegetation.

Although many studies have addressed various aspects of soy cultivation systems for biodiesel production in Latin America [103–106] only few have accounted for LUC [105–109]. This is not surprising since the use of fallow land was usually assumed. Indirect LUC emissions have not yet been addressed. Assessment of the potential impact of direct land-use change (DLUC) effects requires exact knowledge of the carbon stock change. Castanheira et al. [107] have addressed the implications of 35 distinct scenarios of cultivation systems (differing in soil type, soil management and climate) and DLUC on the life-cycle GHG balance of soybeans produced in Brazil and Argentina. GHG emissions vary considerably, from 0.1 kg CO_2 eq/kg soybeans (for NT production in previous degraded grassland, Argentina) to 16.5 kg CO_2 eq/kg soybeans (for production with tillage in previous tropical rainforest, Central West Brazil). As expected, all the tillage systems have higher GHG emissions than the corresponding no- (or reduced-) tillage systems. Relatively low GHG emissions (<3 kg CO_2 eq/kg) are observed for conversion of grassland to soybean plantation (no-tillage). The original land choice is a critical issue in the sustainability of soybean production and degraded grassland is a preferred choice. While some LUC effects, such as production of biodiesel feedstock on degraded lands, mitigate GHG emissions, cultivation on such lands will lead to sub-optimal yields. In most cases, the effect of alternative land-use strategies on carbon stores leads to a net increase in GHG emissions of biofuels when compared to fossil fuels. Control mechanisms should be enforced when (negative) effects are ascertained. The effects of biodiesel production on ILUC are still very uncertain and there is lack of appropriate methodology [110]. The problem of undesired land use and ILUC must be solved *before* stimulating a substantially larger scale supply of biofuel [108].

Land-use transitions in Latin America are twofold: (i) accelerated deforestation in areas suitable for modern agriculture (*e.g.* soybean), reflecting increasing global demand for food, feed and biofuels; and (ii) abandonment of marginal and grazing lands, as a result of rural-urban migration [111]. Cropland conversion is taking place largely in forest ecosystems. A major source of uncertainty is emissions from deforestation and changing land use. Because forests store carbon in their biomass and soils, deforestation is contributing somewhere between 8% and 25% of total annual global carbon emissions [112,113]. The annual rates of tropical deforestation from Brazil and Indonesia alone have nullified for 80% the emissions reductions gained by implementing the Kyoto Protocol in its first commitment period [114]. Increasing global integration of markets and demand for agricultural commodities appears to be driving substantial increases in deforestation rates. Recent studies [115,116] suggest that deforestation is decreasing.

4. US soybean agriculture

Seen in historical perspective US agriculture has witnessed land-use change with considerable social impacts long ago [117]. Later, in the 1930s the ‘Dust Bowl’ hit the United States when rapid but technologically inconsistent expansion of the agricultural frontier made farming unsustainable by severe soil erosion. The dust storms degraded about 91 Mha of Midwestern land [118]. This experience has prompted the development of reduced tillage practices to improve soil coverage and promote sustainable productivity growth. Zero-tillage technology, however, has become possible only when selective herbicides became available, as weed control is the main obstacle in switching from conventional to no-tillage practices.

At present, the United States is the world's biggest producer of soybeans (34% of global production) and soybean products (*cf.* Table 4). More than 80% of US soybean acreage (forecast of 73.0 M acres in 2013) is concentrated in the upper Midwest (with highest yields and lowest costs) with some significant amounts also in the Delta and Southeast. Soybean production in the 16 most productive US states (all with >1 Mt in 2011) amounted to about 80 Mt. Top producing states (>6 Mt, 2011) were IA, IL, MN, NE

and IN (in this order). Harvested soybean acreage per US farm was 229 acres (92 ha) in 2007. Irrigation was used on 2.1 Mha or 8% of US soybean acreage in 2007 (mainly in AR and NE); the irrigated/non-irrigated yield ratio amounted to 1.33.

The US Midwest is a very intensively managed agricultural area. US soybean is mostly produced in two-year crop rotation with corn, as typical for the Midwest *cq*. Corn Belt region [119,120]. Continuous soybeans are not a common occurrence in Iowa as two or more years of continuous soybean create serious problems with soybean nematodes – *Heterodera glycines* [121]. In Iowa cropped acres are mostly under mulch till whereas highly erodable land is under no-till. Soybean double-cropping with corn is not possible because of the short growing season. Double-cropping with winter wheat as the first crop and soybean as the second crop is being practised in certain US states (VA, OK and NC). However, cropping with wheat in the South is declining. In 2011 about 6% of the US soybean planted acreage followed winter wheat [122].

Currently, a shift of soybean production out of the Corn Belt is taking place as a result of high corn prices [102]. This will severely impact US soybean acreage and crop rotation choices. The shift in rotations is tied to shift in tillage, determining corresponding environmental impacts. The changes in crop rotations as a function of corn prices are directly reflected in changes in nitrogen fertiliser application. Secchi et al. [102] have considered the impact of the land-use changes on four important environmental indicators: sediment losses, nitrogen losses, phosphorus, and carbon. High corn prices force highly erodable land to no-till regions, with highly negative environmental effects. Increased corn acreage in the US will reduce soybean production and might encourage soybean expansion in South America, locally inducing deforestation processes. The impact of such ILUC on GHG emissions of soy biodiesel is expected to be significant.

Table 8 shows the fertiliser inputs to US soybean and corn production. Nitrogen is essential to agricultural sustainability. Soybeans can be produced with nearly zero or without nitrogen. Only about 18% of the total US soybean crop comes from N-fertilised fields. Nitrogen application relates to soil N content and crop yield. The nitrogen application rate is about 27 lb/ac fertilised. Nitrogen and pesticide requirements for producing 1 L of ethanol eq (Le) from soybeans in US conditions are approximately 29 g N/Le and 2.6 g/Le, respectively, or 46 g N/L biodiesel and 4.0 g/L biodiesel [75]. Best N management practices positively affect profitability and soil and surface water quality but poor management may lead to environmental contamination. Crop nutrition, fertilisation and soil erosion have heavily contaminated aquifers in the United States. The average N lost from soybean fields to surface waters through runoff, sediment transport, *etc*. is about 30% of the N fertiliser applied [75]. Excessive N application or poor N management in Midwestern agricultural basins that have surface drainage have been linked to increased nitrate loading in the Mississippi river [123] and to nitrogen enrichment in the Gulf coastal waters (leading to hypoxia). Nutrient overloading, particularly nitrogen and phosphorus from fertilisers, animal wastes and sewage, leads to algal blooms and eutrophication. Remediation requires using fewer fertilisers and/or adjusting the timing of fertiliser applications to limit runoff of excess nutrients from farmland. Poor fertiliser management (timing, application rates) is also linked to increased nitrous oxide concentrations, which contribute to ozone depletion and the greenhouse effect [124]. Malone et al. [120] and Adler et al. [80] have modelled N management of Midwestern and North-eastern corn-soybean and corn-soybean-alfalfa rotations.

Table 8
Fertiliser inputs (kg/ha) to soybean and corn production in the United States.

	Soybean	Corn
Nitrogen	3.7	153
Phosphorus	37.8	65
Potassium	14.8	77
Yield (kg/ha)	2668	8655

After Ref. [33].

In recent years, an increasing number of soybean farmers has adopted conservation tillage practices. The estimated US soy planted acreage with no-tillage operations amounts to 38.5 million acres or 49.8% (2009) [125]. The development of better herbicides has allowed producers to use less intensive soil cultivation practices. Pesticide use data (2005) for US soybean are as follows (referred to 26.24 Mha harvested area): herbicide 35,085 t; insecticide 1086 t; and fungicide 87 t. All US weighted average amounts to 1.34 kg pesticide/ha [126]. US farmers do hardly apply any insecticides or fungicides on soybeans as a routine part of pest management as insects and plant diseases rarely damage US soybean cultures.

The United States is also the leading producer of biotech crops in the world. In 2011 93% of US farmers used herbicide-tolerant biotech soybean crops (*cf*. 57% in 2002), most of which were Roundup Ready® (RR). Monsanto has procured itself a disproportionate control of the US soybean seed market, at least until the time of the patent expiration (2014). Meanwhile Roundup Ready 2 has been developed (available from the 2011 season). Yields of conventional beans in the US tend to be lower than those of GM seeds. Segregation of the conventional bean supply chain is not cost-effective in the United States. Verdeca, a US-based joint venture between Bioceres (Rosario, SFE) and Arcadia Biosciences, Inc. (Davis, CA) is developing and deregulating soybean varieties with next-generation agricultural technologies. Verdeca focuses in particular on traits that increase soybean adaptability and yields by combining Bioceres' drought tolerance technology and Arcadia's nutrient efficiency technology. It is noticed that Nitrogen Use Efficiency (NUE) canola can achieve high yields using significantly less nitrogen fertiliser than conventional varieties. The first products from the Verdeca technology platform are anticipated to reach the market between 2015 and 2017.

4.1. US soy biodiesel

In 2010 the US soy oil production amounted to 8.6 Mt and exports to 1.5 Mt (with negligible imports). About 12% of total soy oil was converted into soy biodiesel. Feedstock for US biodiesel is about 50% SBO (2011) with animal fats and yellow grease, inedible corn oil, and canola oil comprising the remainder of production. The United States has registered a record biodiesel production of 3.2 billion litres (mainly from soybeans) in 2011 and is now the world's top producer. The recent dramatic increase in US biodiesel production is due to a government mandate in mid-2010 that required refiners to blend 3.1 billion litres (800 million gal) of biodiesel with diesel in 2011. At present, biodiesel production is aimed primarily at the domestic market, although exports to the EU have been the main driver in the past few years. However, lately US biodiesel exports to Europe have dropped considerably from 1 Mt (2007) to 250 kt in March–December 2009 and to only 150 kt in January–September 2010. The US Environmental Protection Agency (EPA) proposals for the 2012 requirements under the Renewable Fuel Standard (RFS2) are as follows: biomass-based diesel (1 Bg, 0.91%), advanced biofuels (2.0 Bg, 1.21%), cellulosic biofuels (3.45–12.9 Mg, 0.002–0.010%), total renewable fuels (15.2 Bg, 9.2%). The US has set a target of 36 Bg biofuels by 2022.

Although US agriculture is generally seen as an example of GAP, this has not always been the case (*cfr*. Section 4). Nowadays, US agriculture is faced with severe eutrophication in the Gulf of

Mexico by leaching of nitrates as a result of excessive use of fertilisers in the Corn Belt.

The EU-RED sets various sustainability requirements to biodiesel production from vegetable oils. In particular, EU-RED has two requirements that negatively affect import of US soybeans. To be eligible for EU tax credits and use mandates, biofuels must reduce GHG emissions by a minimum of 35% compared to petrodiesel, by 2013. RED establishes default values for emission savings for each biofuel based on the feedstock used. The default value for soy biodiesel is 31%, *i.e*. less than the minimal 35% requirement. The former value was determined using production, processing, and transportation data for soy from Brazil. Addressing US compliance with the GHG reduction requirement is further complicated by the EU's intention to recalculate emissions savings taking ILUC into account. The United Soybean Board (USB) has recently shown that the actual emissions savings from US soy biodiesel are 56% [127,128].

The second RED requirement is that feedstocks used to produce biodiesel must be certified as having been produced sustainably on land that has not been converted from rainforest or other high carbon density conditions. This is indeed not the case in US agriculture. At variance to some Latin American countries, an expansion of land area devoted to soybean for biodiesel use in North America is also less likely because of increased competition for land by the corn ethanol industry.

As US farm law requires conservation compliance, including stewardship practices which meet RED standards, US productions should qualify for eligibility under the RED requirements. However, with almost no adoption of any certification scheme for biofuel produced in the United States full implementation of EU-RED could adversely affect US producers of biodiesel, and soybeans exported and crushed in Europe for biodiesel. Certification is to be carried out by companies in compliance with one of several EU-approved schemes (*cf*. Table 25) under which the production, shipment, and processing of the feedstock can be traced in order to verify compliance with sustainability requirements. The American Soybean Association (ASA) is supporting efforts for certifying US compliance with the sustainable land use requirements of the Renewable Energy Directive [129].

5. Soybean crop in Brazil

Due to its great biodiversity and diversified climate and soil conditions, Brazil has many vegetable oil sources, including soybean, castor seed and palm-tree oils. Brazil's climate favours soybeans. Moreover, soybeans can grow and produce well in relatively poor tropical soils. Soybeans are the backbone of Brazil's agriculture and the soybean industry is considered to be of critical importance to the national economy. The country is a significant agricultural exporter since 2000 [130]. The agribusiness sector accounts for about 35% of Brazil's GNP. Brazil is now the world's second-largest soybean producer (about 25% of global production) and exporter, after the United States (*cf*. Table 4). These countries are counter-seasonal suppliers. Brazilian exports of soybeans (29.95 Mt, 2010/2011) account for 32% of global exports [30]. Although Brazil faces rising domestic demand, Brazilian agricultural production potential and exports can show further significant growth as large areas of untapped agricultural land remain. Low on-farm production costs make Brazil a competitive exporter of soybeans.

In Brazil, soy plantations operate both as monocultures and in crop (typically corn) rotation mode (very useful to mitigate disease and pest occurrence). The usual soybean agricultural production methods in Brazil are characterised by conventional no-tillage management with intensive use of fertilisers, agrochemicals and agricultural machinery. Direct seeding has become widespread. Soybean expansion in relation to export of soy products and to increasing cattle production has led to deforestation [3].

In 2010/2011 soybean crop was the largest in Brazil's history, with a production of 75.5 Mt. This record was due to the increase in cultivated area and to higher yield. Soybean production forecasts 2012/2013 are 77 Mt on a total area of 26 Mha with an average yield of 2.96 t/ha [131]. Both Brazil and Argentina have matched US average yields and continue to rise with improved seeds, rapid adoption of the latest production and machine technology and better soil management techniques. In addition, higher fertiliser use has aided yield increases in recent years. Brazilian soybean farmers apply on average 500 kg fertiliser as well as high other chemical inputs (lime)/ha (up to 3200 kg/ha) [30]; *cf*. Table 8 for US fertiliser inputs. In 1995 Brazil used no N fertiliser application and relied totally on BNF [132]. The input of fixed N for soybean production in Brazil is estimated to be 170 kg/ha of harvested soybeans [133]. A common NPK fertiliser rating used in fertile Southern Brazil is 02-20-18, applied as 202 lbs/acre (or 226 kg/ha) [134]. By selection of genotypes for maximum BNF fertiliser N is no longer needed for soybean production in low fertility Brazilian soils [132]. Fertiliser use in Brazil in the 1995–2008 period has increased more strongly (142%) than global average (36%) [135]; consumption is 24.5 Mt (2010). Brazilian soybean cultivation accounts for 3.8% of total Brazilian N use, 41.3% P_2O_5 use and 34.7% K_2O use (2007/2008).

Brazil's tropical climate requires improved pest and disease management. Pesticide application in Brazil is necessarily higher than in the United States. In 2001–2003 soybean rust (*Phakopsora pachyrhizi*), a fungus-caused disease, has been devastating to Brazilian crop [136]. Measures to combat the disease involve double-cropping corn following soybeans or spraying soybean plants with large amounts of (expensive) strobilurin or triazol fungicides. Brazil's Agricultural Research Corporation (Embrapa) has developed a new rust-tolerant seed variety [137]. Effective nematode resistant varieties are under development by Monsanto Co./Divergence, Inc. [131].

All regions in Brazil produce soybeans, but soybean plantations are mainly located in the South-Southeast and Central-West regions (Table 9). Mato Grosso (27%) and Paraná (20%) are the main national producers with the former accounting for 8% of global soy production. In Brazil, soybean production concerns largely soils that have recently been taken into agricultural use. Much of the recent agricultural expansion has taken place in Centre West and also in the North (including the Amazon basin). The expansion of Brazilian soybean production has occurred in the Cerrado ecoregion [133,138], and has also replaced tropical rainforest [139,140]. Rapid area expansion was largely accomplished through the wholesale clearing and conversion of virgin savannah land [141]. Protected areas cover only 1.7% of the Cerrado and 4.6% in Amazonia. Whereas the clay-rich soil in the southern region of Brazil is naturally conducive to soybean production, the sandy soils in the Central-West region have a low pH (on average 5.0) and

Table 9
Soybean production (kt) in Brazil by region (2009/2010).
Source: Instituto Brasileiro de Geografía e Estatística (IBGE).

Centre-West	31,609
South	25,685
Northeast	5304
Southeast	4298
North	1623
Total	68,519

SIDRA database.

poor nutrients and need to be balanced by lime and enriched with other minerals to be productive. Soluble soil phosphorus content of about 0.4 ppm is far below recommended levels for plant growth. Potassium availability is mostly low as well. Organic matter content of the soils is moderate to high but with low cation exchange capacity, resulting in sensitivity to leaching. Cerrado soils are also sensitive to erosion. Exploitation of the Cerrado for soybean cultivation requires simultaneous liming to raise pH, and applying P, K fertilisers (at twice the rate used in Southern Brazil) in a no-tillage system.

Agricultural development in the Cerrado (204 Mha) with its extremely acid, nutrient-poor and degradation-prone soils has been made possible, thanks to soil management techniques and new soybean varieties developed by Embrapa [142]. Through the development of high-yielding tropical varieties and the availability of vast areas of Cerrado land, 60% of Brazilian production is now coming from tropical states [3]. The developing agriculture in the Cerrado is on a large scale and well mechanised [143]. The soybean crop is sown in October or November when rain sets in which makes nutrients and limestone sink deeper in the soil. Cerrado soybeans are mostly grown in rotation with maize and winter wheat, but also with soybean. In view of erosion problems, reduced tillage operations are being used most frequently. However, these methods increase the need for herbicide treatment; also insecticides are used rather extensively. Many agrochemicals used are very toxic and not allowed in European agriculture.

Brazil became a large soybean producer during the 1970s/1980s, when soybean varieties adaptable to warmer climates were developed by Embrapa [144]. With the introduction of new methods for enhancing soil conditions, the Brazilian Cerrado in the central and northern regions became suitable for growing soybeans. In 2010, Central-West (MT, MS, GO, DF) accounted for 46% of Brazil's total production, averaging 2.9 t/ha. Future soybean expansion will rehabilitate 20 Mha of degraded pastureland in the North and Northeast (MA, TO, PI, BA).

The development of lower-latitude (warmer) soybean varieties in Brazil by Embrapa is one of the most significant innovations in the agriculture of the Green Revolution [145]. Short-cycle soybean varieties permit double-cropping, while the adaptation of no-till planting reduces long-term costs from soil degradation. Brazilian crop researchers have succeeded in breeding high-yield soybean varieties for every climate region in the country, including tropical varieties for the equatorial lowlands. Soybeans had not previously been suited to areas with high rainfall. The humid Amazon climate does not inhibit soy cultivation (often in a rice-soy sequential cropping system). A new Brazilian soybean variety, BRS-Raimunda, yields an average of 5 t/ha/yr under normal Cerrado field conditions. Embrapa has also researched legumes and bacteria to fix nitrogen in Brazilian soils in order to lessen the need for imported fertilisers. Since 1970, Brazil's soybean production has increased from 2 Mt to 24 Mt in 1995. This was only possible due to plant breeding for N_2 fixation and to the development of new *Rhizobium* inoculants which had been adapted to the specific microbial disequilibrium prevailing in the soils of the central highland savannah (Cerrados) after they have been ploughed, limed and fertilised for cropping. Brazil is the only country that does strain selection of rhizobia to increase N-fixation, which is highly successful in eliminating the need for nitrogen fertilisation.

Despite the fact that the Brazilian government banned the use of GM soybean varieties in Brazil in 1999, at least 10% of the Brazilian soybean area in 2002 was supposed to be GM through illegal imports from Argentina [146]. Introduction of GM RR soy has been much slower than in Argentina and Paraguay. Brazil now allows GM seeds and applies an efficient regulatory process for adopting new seed varieties. The Brazilian government has approved 33 distinct GM crop varieties since 1998, including GM soybean [147]. Brazilian authorities gave approval for commercialisation of Roundup Ready® (RR) soybeans only in late 2003. The biotech adoption rate of GM soybeans reached 80% in 2011/2012 (expectations of 85% on 21.4 Mha for 2012/2013). The new Intacta RR2 PRO variety (Monsanto), specifically developed for Brazil, possessing herbicide resistant, pest resistant and yield boosting characteristics, has been pre-launched in 2012 [122]. Monsanto charges Brazilian farmers a fee of R$115/ha for the use of the new Intacta RR2 PRO event. The development of region-specific soybean varieties is advancing with a double-stacked variety involving a biotech Roundup Ready® event coupled with a non-biotech rust tolerance trait. An alternative to RR varieties has been developed by BASF/Embrapa (marketing for 2012/2013 season) [131]. Acceptance of biotech crops in Brazil is strong among producers (with 31.8 Mha in 2011/2012), but low in the food processing industry and by consumers. Table 10 lists the soybean biotech crops approved for use in Brazil.

Brazil grows both conventional (non-GM) soybeans (40% of total Mato Grosso's production in 2011) and GM soybeans (southern states are virtually 100% GM). This product differentiation gives Brazil an advantage over its competitors in markets that demand non-GMO feedstocks, notably EU-27. Conventional soybeans must be segregated all along the marketing chain to the end-users in order to be sold at a premium over GM product [30].

USDA Agricultural Projections to 2018 indicate that Brazil will need to produce 43% more oilseeds from 2008 level to meet domestic and foreign demands [148]. USDA also forecasts that by 2018 an additional 10 Mha of cropland in Brazil will be brought into production [30]. Expansion of soybean area is occurring very fast, mainly through degraded pasture lands in the Cerrado. About 60% of currently degraded pasture lands (72 Mha) can be converted to crop production. However, as agricultural land moves to

Table 10
Soybean biotech crops approved in Brazil.[a]

Trait category	Trait description	Applicant	Event	Crop year
Herbicide tolerant	Glyphosate tolerant	Monsanto (Monsoy)	Roundup Ready® GTS-40-3-2	2008
Herbicide tolerant	Herbicide tolerant Imidazolinone class	BASF Embrapa	BPS-CV 127-9	2009
Herbicide tolerant	Glufosinate ammonium	Bayer CropScience	Liberty Link® A5547-127	2010
Herbicide tolerant	Glufosinate ammonium	Bayer CropScience	Liberty Link® A2704-12	2010
Herbicide/insect tolerant	Glyphosate tolerant	Monsanto	MON87701 × MON89788 (Intacta RR2 PRO)	2010
	Insect resistant			

After Ref. [147].

[a] For food and feed.

marginal lands where the climate is less favourable to land-intensive practices, productivity and output will be reduced. Brazil, which possesses 20% of the planet's freshwater, has tremendous potential to expand planted area via irrigation projects that make possible second crops rotated over a yearly growing season. Large irrigation project investments are increasing soybean planted area through rotating cash crop production. Irrigation improves yields and quality but increases cost.

The Brazilian agribusiness structure comprises both small (30–60 ha) producers in the South and North – organised as cooperatives and not dissimilar in size from typical Midwestern US farms – and mega farming operations in the Central-West region (as large as 50 kha), allowing economies of scale [30,149]. Soybean production in Brazil takes place in two main farming modes (in approximately 1:3 ratio), namely: (i) small, family managed farms using several production systems (Southern states); and (ii) huge farms with monoculture production (Cerrado). Grupo Bom Futuro is the world's largest soybean producer with an equivalent farmed acreage of about 0.4 Mha (accounting for double cropping). Brazil's large farm sizes facilitate traceability (*e.g.* of non-GMO soy) to the exact growing locations.

Brazil's low-cost resource base, significant areas of underutilised arable land and ample water resources, as well as weather patterns across much of the country, which permit intensive land use (including double-cropping in many regions), enables high-yielding crop production at low on-farm production costs. Beans are harvested as moisture reaches 18%. After the summer crop harvest 'out-of-season corn' is planted immediately. Soybeans produced in Brazil are cost-competitive with those of all major producers. Brazil's agricultural research system is one of the most developed in the world. Embrapa's activities have also concerned techniques for the integrated management of diseases and pests, irrigation management, and the bonification and fertilisation of the soil [150]. This has resulted in a large increase in agricultural yields and expanding production in the Cerrado. Brazil's impressive agricultural performance of the past is likely to continue.

At the downside (Table 11), Brazil's soy agriculture also suffers from several disadvantages. In tropical regions more herbicide and fungicide use (several sprayings) is often required than in more temperate climates (*e.g.* USA). Diseases like rust, powdery mildew and white mould are becoming a problem. Other disadvantages connected with Brazil's soybean sector include large areas of soil with poor nutrients that require large volumes of imported fertiliser to maintain yields, and an underdeveloped transportation infrastructure with large distances from production areas to the domestic consumer or to warehousing facilities and port terminals for export.

The development of Brazil's transportation infrastructure has been lacking behind the rapid growth of the soybean industry and production forecasts continue to outpace improvements in transportation and infrastructure [131]. Quite at variance to Argentina, Brazil's inland production regions are far from harbours and waterways, as well as from major domestic markets. Currently 85% of soybeans for export still leave through Brazil's southern ports, far from export markets. Domestic transportation costs are considerable: transportation of soybeans harvested in Mato Grosso accounts for 25–30% of total cost at the port of export, as compared with only 8–10% for soybeans harvested and transported in the United States and 4–5% in Argentina [30]. These differences are found back in LCAs. While better roads and highways represent a huge logistical benefit for soy farmers, at the same time they may also lead to additional destruction of formerly remote areas by accelerating other harmful activities such as logging and cattle ranching [151]. In this way, soybeans in Brazil and their associated massive transportation infrastructure catalyse destructive processes causing collateral damage. Specific infrastructure projects have excessive impacts. Mega infrastructure projects are at the origin of the world's highest rate of forest destruction in Amazonia [152].

Table 11
General characteristics of the Brazilian soybean sector.

Advantages
• Low on-farm production costs
• Economy of scale
• Low land costs
• Low seed costs
• Intensive land use
• High yield
• Multiple crop plantings/yr
• Large areas of untapped agricultural land
• Tropical weather pattern
• Rich water resources
• Globally cost-competitive (export)
• Diversificated farm sizes
• Differentiated products (conventional and GM)
• High agricultural production potential
• Highly developed agricultural research
Disadvantages
• Large areas of poor soil
• Need for fertilisation
• High costs of fertilisers and chemical inputs
• Loss of energy and nutrients (through export)
• Disease prone conditions
• Large distances
• Underdeveloped transportation infrastructure
• High inland transportation and ocean freight costs
• Environmental threat (deforestation, biodiversity)

Soybean cultivation in Brazil is viewed as a threat to the environment, in particular in terms of soil erosion and tropical biodiversity [151]. Soybean expansion has been associated with logging, charcoal production and pasture development, three critical causes of tropical deforestation and habitat loss [153]. Brazil's government policies have facilitated soybean expansion to critical habitats rather than exploit the vast areas of degraded land. Much of Brazil's soybean expansion has replaced natural biodiverse vegetation, despite the existence of some 10 Mha of degraded pasture or deforested land.

Brazil's export of soybean and its products in relation to increasing cattle production has led to deforestation [3]. Brazil ranks first in tropical deforestation in the world and lost 23 Mha of forest before 2000 alone. Intensive mechanised agriculture in the Brazilian Amazon grew by >3.6 Mha during 2001–2004 [154]. Mato Grosso is the Brazilian state with the highest deforestation rate (17% of forest lost since 2001) and soybean production [155]. Pasture remains the dominant land use after deforestation. Continued expansion in the Cerrados and in the Amazon region, which plays a vital role in terrestrial carbon storage [152], is constrained by environmental concerns about land clearing. The future expansion in cropland is likely to come mostly from converted pasture land [156]. South America has lost 4.3 Mha/yr between 1990 and 2005. Brazil is responsible for 42% of the net loss of global forest [157]. Satellite-monitoring programs (PRODES, DETER, FORMA) and environmental certification schemes (*e.g.* Soy Moratorium) contribute to reduction of illegal deforestation.

It is more profitable to process soybean in Brazil and sell more finished products in the international market. Most Brazilian exports are in the form of whole beans (40% in 2010/2011; *cfr.* 19% for Argentina). Argentina focuses on the export of soy meal. The most important markets for Brazilian soybeans are EU and China. Europe imports about 70% of Brazilian soybean exports, mainly for use as soy meal for livestock production. Brazil is the world's largest conventional (non-GM) soybean producer, which

accounts for 20% of total production in 2010/2011 [30]. As a result of increased domestic consumption between 2006/2007 and 2010/2011 the share of Brazil's domestic soybean oil production that was exported fell from 41% to 24%. About 75% of Brazilian soybean oil is thus consumed domestically. Domestic soybean oil demand (5.26 Mt, 2010/2011) is expected to grow by 150 kt/yr, based on Brazil's 5% biodiesel blend mandate (as from January 2010) and is forecasted to increase further in 2013 should a B7 biodiesel blend be introduced [131]. Production of biodiesel accounts for about one-third of soybean oil consumption in Brazil.

Few LCAs deal with the processing of soybean oil [158] and few describe environmental assessments of Brazilian soy biodiesel including land-use effects [104,106,159–161]. Emergy analysis has been used to evaluate the soybean production system and industrialisation stages [103,104,162]. Brazil loses a great amount of emergy and nutrients by producing raw soybean and soy meal for international markets. Depletion of natural resources (annual loss of about 2.3 Mt N, P or an equivalent of 5.7 Mt in chemical fertilisers) in Brazil is not compensated for and creates an ecological debt. Consequently, exporting soybean as a commodity results in a low profit per unit area.

5.1. Soy biodiesel in Brazil

Brazilian Patent No. PI-8007957 (1980) is the first patent issued worldwide for biodiesel (originally called Prodiesel) [163]. In 1981/1982 some 300,000 L of Prodiesel, produced in the PROERG (Produtora de Sistemas Energéticas Ltda.; Fortaleza, CE) industrial pilot plant with an hourly capacity of 200 L of vegetal diesel were supplied to various Brazilian diesel motor producers. Feedstocks tested included soy, rapeseed, sunflower, palm (dendê), babassu, peanut and cotton oil, as well as fish oil and even oil from maracujá. For various reasons, such as petroleum prices on the world market and lack of interest by Petrobras, the experimental production of Prodiesel was interrupted and the PRO-ÓLEO plan (production of vegetable oils with carbureting purposes) of 1980 was abandoned in 1986.

After biodiesel had stopped being a purely experimental fuel, the initial phase of industrial soybean ethyl ester (SBEE) started in November 2000 in Mato Grosso State with a production of 1400 t/month [164]. In 2002, ethanolysis of vegetable oils was considered as the main route to the PROBIODIESEL petroleum diesel substitution programme and in 2003 introduction of fatty acid ethyl ester-based B5 was prospected for 2005 and of B20 within 15 years [165]. At the end of 2004 the Brazilian Government launched the National Program of Production and Use of Biodiesel (PNPB) with the objectives to diminish dependence on conventional diesel and to implement the production and use of biodiesel in a sustainable way, both technologically and economically, with a focus on social inclusion and regional development through job and income creation [138]. The most important action from PNPB was the introduction of biodiesel in the Brazilian energy matrix by means of Federal Law No. 11.097 (13 January 2005), which established biodiesel mandates, initially B2 with B5 to be reached in July 2010 (*inter alia* to make better use of the installed production capacity). SoyMinas' first commercial medium-scale biodiesel operation (10.6 kt/yr) was located in Cássia, MG (2005). Meanwhile, the Brazilian biodiesel productive chain has been structured. The amount of biodiesel required to fulfil the domestic B5 mandate is now estimated at 2.6 BL. Projections indicate a 4.47 BL (or 3.95 Mt) biodiesel volume for 2020 [166], but a gradual move to 20% blends in big cities would raise annual biodiesel consumption to 5.5 Mt already by 2015. For the history and policy of biodiesel in Brazil, *cf.* refs. [138,163].

The Brazilian biodiesel market and production are regulated by the government through a public auction system which sets the volume of biodiesel to be produced and establishes the average sales price. The auction system gives preference to producers with the so-called Biodiesel Social Fuel Stamp (SFS) [167]. Apart from the mandate, government support for biodiesel also consists in federal tax exemptions (Federal Law 11.116/2005) and incentives differentiated according to the nature of the raw material (soy, palm or castor oil, *etc.*), size of producer (from smallholder agriculture upwards) and region of production in order to encourage biodiesel production and promote social inclusion. The SFS program is a socio-economic mechanism to provide incentives for family farmers in disadvantaged areas such as the semi-arid Northeast and Amazon regions (*cf.* Section 5.2). SFS promotes regional development of agricultural communities and allows better credit terms to the biodiesel producer companies – rated as socially friendly – that purchase (regionally differentiated) minimum quota of raw material from small farmers [168]. At present alternative crops other than soy (such as canola, sunflower, castor bean, palm, tung) have small local productions only and do not have surplus [169].

Although PNPB aims at promoting small-scale farming (in particular in the Northeast) so far between 75% and 95% of the biodiesel production in Brazil comes from soybean grown on plantations controlled by large-scale farmers at production costs higher than those for fossil diesel [170,171]. Comprehensive assessments of labour conditions, land division, food prices, and other socio-economical implications arising from the expansion of biofuels in Brazil are yet to be carried out.

Soybean is the most important feedstock used to produce biodiesel in Brazil [172]. Biodiesel production 2011/2012 of 2850 ML (or 2.5 Mt at B5 level) originated from soy (84%), tallow (15%) and cottonseed oil (1%); *cf.* mineral diesel consumption (or 40% of total fuel consumption) of 49.24 BL. At a domestic consumption of 2830 ML exports (0.1%) and imports (0.4%) were negligible. Existing capacity of biodiesel production consists of 75 industrial units with a total nameplate capacity of 6750 ML (or 5.9 Mt) and a capacity use of 42% (*cf.* 10% in USA, 40% in EU and 55% in Argentina). Petrobras is responsible for biodiesel blends and hence the only buyer of biodiesel. Raw materials make up approximately 75% of the Brazilian biodiesel production costs.

Brazil is a global leader in the use of renewable fuels (44.8% in 2010, 46.3% in 2020), mainly bioethanol; its policy directives include an increase in the biofuels' share in the national energy matrix. Although to date no significant biodiesel exports have occurred Brazil can potentially become a net exporter in view of excess industrial capacity. However, this is not expected to occur in the short and middle term. Despite EU restrictions the country would have few difficulties in establishing export markets [12]. Brazil's government and biofuel industry are planning a large increase in the production of biofuels by 2020. Soybean plantations already occupy 35% of the country's cultivated land [173].

The Brazilian biodiesel standard ANP 42 (2004) differs from the European EN 14214 and US ASTM 6751 in several respects. Differences with regard to EN 14214 for soybean concern IV, oxidation stability and CFPP. Brazilian B100 soy biodiesel does not comply to the European standard, but blending is a realistic option. Development of worldwide biodiesel standards and international harmonisation are actively being pursued [174].

5.2. Brazil's soy policy

Although Brazil is already a global key producer of soybean and its derivatives, the country will need to increase its production considerably (43% from 2008 to 2018) to meet projected domestic and foreign demand, particularly for biodiesel production [149]. This requires further exploitation of its relative land abundance.

The use of protected lands is restricted and rehabilitating marginal land is limited both in terms of technology and cost.

Brazil is well aware of the strategic need to produce its soy export commodity in a sustainable way and actively pursues good agricultural practices [175]. Table 12 lists a selection of domestic initiatives. Soja Plus is a voluntary social, economic and environmental management programme which targets rural producers. The programme focuses on labourer conditions and occupational health, improved agricultural production practices, product quality, economic feasibility, quality of life and social responsibility [176]. Soja Mais Verde is an initiative of the soy producers of the State of Mato Grosso (APROSOJA) and an international NGO (The Nature Conservancy, TNC) with the objectives of producing sustainable soy in Mato Grosso and mapping of rural properties [177]. Various other programmes are aimed at GAP [178] and at quality improvement of agricultural products [179]. The Brazilian Programa Soja Livre (Embrapa) aims at meeting the needs of producers of conventional soy in Mato Grosso State [180]. Soja Livre (Free Soy) in an initiative to pursue development of commercially competitive non-GE varieties to secure Brazil's role as the largest non-GE soybean producer and exporter to the world. Some regional (Centre-West) non-GE varieties possess higher potential productivity than GE varieties.

Since its launch in 2005, the Brazilian soybean sector has been active in the Round Table of Responsible Soy (RTRS), *cfr*. Section 10.1.2. Various corporate industrial initiatives are worth mentioning (Table 13). Grupo André Maggi (Brazil) is a constituent member stakeholder in RTRS and Soy Moratorium, and takes part in the GRES (Grupo Referencial de Empresas em Sustentabilidade) project (Instituto Ethos). Bunge also participates in RTRS and the Soja Plus program.

Several Southern Brazilian states (PR, RS, SC) give full support to agricultural sustainability, but more widespread adoption of sustainable agriculture is auspicated. In this regard, several significant initiatives deserve mentioning. Recently, the implementation of environmentally effective and economically efficient agri-environmental policies have become a top political priority in Brazil [189]. Brazil is taking voluntary actions to reduce GHG and other pollutant emissions between 36.1% and 38.9% by 2020 from 2010 values. The Low Carbon Agriculture Plan (Plano ABC), adopted in 2010 as one of the 12 sector plans of the Brazilian National Climate Change Policy (Federal Law 12.187/2009), is an ambitious federal programme of the Ministry of Agriculture, Livestock and Supply (MAPA), which aims to combine food production and bioenergy in reducing gasoline engine emissions (GEEs) from the agricultural sector by 133–166 Mt CO_2 eq by 2020. Great consideration is given to the use of internationally recognised and approved methodologies of carbon mitigation. Secondary environmental objectives are improvement of GAPs (comprising soil quality and protection), adoption of Sustainable Production Systems, and reduction of deforestation. Table 14 shows the ABC plan environmental targets. The programme requires technology transfer to small farmers in the coming years. One of the major proposals of the ABC program relates to the recovery of degraded pastures. The goal is to convert 15 Mha of such degraded areas into productive land.

In the framework of land-use policies, Brazil's forest code places restrictions on land use with the intention of regulating and limiting deforestation. Although environmental restrictions invariably increase the cost of agricultural production, certain customers are willing to pay a premium for sustainably produced goods. For example, in 2009 the Sugarcane Agroecological Zoning (ZAE) has been launched to promote sustainable sugarcane growth and development while preserving the environment.

NGOs have launched discussions on the environmental effects of converting vast tracts of savannah into arable land, in particular for cultivating soybeans. Pasture remains the dominant land use after forest clearing in Mato Grosso but the growing importance of larger and faster conversion of forest to cropland disproves the claim that agricultural intensification does not lead the new deforestation [154].

The Soy Moratorium for the Amazon biome, which represents 49% of Brazil's land mass, is a commitment made by industries and exporters not to acquire soybeans from areas of the Amazon biome illegally deforested after July 2006. Numerous European and US enterprises, such as Ahold, Carrefour, Coop, Kraft, Marks & Spencer, McDonald's, Nutreco, Ritter-Sport, Sainsbury's, Waltrose and Walmart, sustain the programme. Amazon deforestation is Brazil's largest source of CO_2 emissions [114]. One of the major tools to establishing sustainable forest practices is long-term aerial monitoring to regularly assess the condition of forests and to timely identify land-clearing activities at a fairly high level of spatial resolution [115]. For this purpose Brazil operates the PRODES (Amazon Deforestation Monitoring Program) and DETER

Table 12
Brazilian programmes of good agricultural practice.

- Soja Plus
- Soja Mais Verde
- Soluções para Suprimentos Sustentáveis (3S) (Cargill)
- Sustainable Agriculture Code (SAC) (Unilever)
- Program Soja Livre (Embrapa)
- Agricultura Sustentável (Bunge)
- Programa de Aplicação Responsável (PAR)
- Programas de Boas Práticas Agrícolas (Emater)

Table 14
ABC plan environmental targets.[a]

Sub-programme	Targets		Estimated GEE reduction (by 2020)
	2011/ 2015	2016/ 2020	
Degraded pastures renovation (area)	6.0	9.0	83–104
Integrated crop-livestock-forestry systems (area)	1.5	2.5	18–22
No-tillage systems (area)	2.8	5.2	16–20
Biological nitrogen fixation (area)	1.0	4.5	10
Planted forests (area)	1.0	2.0	8–10
Animal waste treatment (volume)		4.4	6–9

After Ref. [190].
[a] Area in Mha, volume in Mm^3, GEE reduction in Mt CO_2 eq.

Table 13
Selection of industrial socio-environmental sustainability initiatives.

- Cargill: Soluções para Suprimentos Sustentáveis (Solutions for Sustainable Supply) (SSS or 3S) [181,182]
- Unilever: Sustainable Agriculture Code (SAC) [183]
- Bunge: Agricultura Sustentável (Sustainable Agriculture) [184].
- Syngenta [185], Grupo André Maggi [186], Fiagril [187]; various socio-environmental sustainability projects
- Abengoa: RED Bioenergy Sustainability Assurance (RBSA) [188]

(Real-time Detection of Deforestation) programmes [191]. PRODES has provided yearly maps of Amazonian deforestation since 1988. Since 2004, these have been augmented by twice-monthly estimates from the DETER system. By using satellite images and panoramic aerial photographs under the Soy Moratorium's monitoring process, supplied by PRODES, 11.7 kha of soybean planting were detected in the 2010/2011 crop year in deforested areas of the soybean producing states in the Amazone Biome, corresponding to 0.28% of all Amazon deforestation (4.19 Mha) [115]. Soybeans planted on deforested land in the 2010/2011 crop year amounted to 0.05% of Brazil's total soybean acreage (24.1 Mha) and to 0.6% of soybean acreage in the Amazon Biome (1.94 Mha). It can be concluded that soybeans do not (no longer) play an important role in this process [115]. The transition from forest to cropland occurs rapidly (for 90% during the year immediately after clearing) [114]. It is of interest to notice that in the first years after deforestation occurs rice is the most common crop, preceding soybean planting which starts in the third year [154]. Mechanisation of both forest clearing and crop production has favoured simultaneous expansion and intensification of land use at the forest frontier. The moratorium on soybean has proved to be an efficient way of preventing deforestation directly caused by soybean production in the Amazon region [115].

Outside of Brazil, FORMA (Forest Monitoring for Action) has been developed [192]. FORMA is a rapid identification system for remote sensing of tropical deforestation based on NASA's MODIS (Moderate Resolution Imaging Spectrometer) – derived analysis of fires and changes in vegetation colour. According to FORMA, reductions in forest clearing have occurred recently most significantly in Brazil [116]. Global large-scale forest clearing in the pantropics, as identified by FORMA, has decreased by 42.3% over the December 2005–August 2011 period and by 51.2% in Brazil. Over this same period Brazil's global share in forest clearing fell from 72% to 61%. Forest clearing in Brazil has declined in southern Amazonia but increased in northern Amazonia (Acre, Amapa, Rondônia).

Several other programmes reflect Brazilian government's efforts in promoting long-term sustainability agriculture:

- The long-standing Socio-environmental Development Program of Family Production (Programa de Desenvolvimento Socio-ambiental da Produção Familiar – PROAMBIENTE) was designed to assist rural households (< 26 ha) with the sustainable use of Amazon resources [149].
- Biodiesel "Social Fuel Stamp" (SFS).
  The domestic Brazilian biodiesel market has been regulated by mandates, as elsewhere. While domestic biodiesel production has been conducted so far mainly according to the interests of the soybean supply chain, the Brazilian government considers socio-economic improvements in the poorest areas of the country as a main priority and a challenge for biodiesel production. The biodiesel "Social Fuel Stamp" (SFS) – created in 2004 – is a certification for biodiesel producers that puts family farming in the biodiesel chain. The programme encourages Brazilian biodiesel producers to purchase feedstock from small family farms and thus allows such producers to differentiate their product. The SFS programme has as principle objective improvement of income, safety for the productive set, family farming and environmental sustainability. Results of this noticeable social programme for biodiesel in Northeast Brazil (with 20,000 rural families participating) are still uncertain. It is doubtful that family agriculture will be able to compete with agribusiness (Argentinean style) to ensure the supply of raw materials.
- As to bioethanol, the RenovAção project provides professional training to sugarcane cutters.

The potentialities of family agriculture in preserving natural resources are discussed by De Oliveira et al. [193]. Many of the multiple environmental, economic and social impacts of soybean expansion are unfavourable to the national Brazilian interest. The costs of these impacts have not been assessed properly [151].

6. Argentina's soybean rush

The Argentinean agricultural and rural sectors have suffered historically from heavy political discrimination and transfer of financial resources to the industrial and urban sectors [14,194]. Soybean export taxes have even been as high as 45% in 2008 [195]. Table 1 summarises the paradox in one of the richest agricultural countries in the world, as further exacerbated by soy cultivation for biodiesel.

Argentina has an impressive agricultural potential and is a leading soybean producer. The country presents a great diversity in climates. The centre and East of the country enjoy a very favourable natural endowment for agricultural production, consisting of a large area of arable land characterised by a temperate climate, and in close proximity of ports. The flat and fertile pampa húmeda (wet pampa) enjoys abundant rainfall. In the western part of the subhumid and semiarid Pampas soybean is grown in rotation with winter annual forage crops. In the past, production systems in this region integrated row crop cultivation and pasture grazing for beef and dairy cattle production. The traditional scheme of restoring soil structure and fertility has changed, either by shortening the cycle with pastures or by eliminating it altogether and switching to continuous cropping. In the last two decades the area under grazed pasture has diminished and row crop production (including soybean) has increased with the adoption of continuous no-till soil management [83]. Between 1996 and 2007 the area planted with soybeans as a second crop has increased from 1.9 to 4.4 Mha. In the same period the Pampean area planted with soybean as first crop amounted to 12 Mha.

Argentinean agriculture has seen several developments. In the 1970s the traditional crop-livestock rotation has gradually been abandoned in favour of intensification schemes. Soybeans were virtually unknown in Argentina in the early 1970s to become by far the most important crop nowadays, with more than half of the crop area. Until the introduction of GM soy in Argentina, soy used to be primarily grown in crop rotation patterns with wheat and maize. These crop rotations are still important practices in Argentina, but most often only by farmers who can afford high machinery and seed input. Monocropping is more common practice among small to medium farmers [196].

As from mid 1990s the production of oilseeds has undergone a rapid increase due to (i) modernisation of agricultural machinery and production technology (zero-tillage, introduction of GM organisms such as GR soybeans, greater usage of fertilisers and agrochemicals); (ii) expansion of the soy frontier by displacing other crops (*e.g.* alfalfa); (iii) marginalisation of cattle and dairy farming; (iv) intensification of land use in the traditional areas (Pampean region); and (v) increase in wheat–soybean double-cropping or 'second-soy' (virtual expansion of arable land) [194]. The new double cropping wheat–soy system with tight planting schedules and the associated practice of burning stubble has led to considerable soil degradation which has triggered interest in improved crop management techniques. Soil conservation programmes (such as FAO/SEAG/INTA/ARG/68/526 and Proyecto de Agricultura Conservacionista, PAC) have tackled the land degradation problem. PAC has promoted crop management techniques aimed at a more sustainable agriculture: a maize–wheat–soybean

rotation; reduced and vertical tilling; nutrient replenishment through fertilisation (mainly N, P); and integrated pest and weed management.

The great versatility of soya for adaptation to different environmental conditions has allowed expansion of its cultivation to other parts of Argentina with greater fragility and higher risk of soil degradation. Soybean acreage has steadily increased from 6.1 Mha in 1996 to 19.0 Mha in 2011 with a production of 53 Mt (Fig. 2). Forecasts 2012/2013 stand at 55 Mt soybeans on a 19.7 Mha soy area [197]. Soybean accounts for approximately 53% of the Argentine agricultural land surface and this share is still rising; 88% of this surface is concentrated in the central region (BA, CDB, SFE) representing 83% of the national soybean production (2008). However, soybean cultivation accounts only for 27% of the total agricultural production capacity (in t). The technical potential of surplus agricultural land in Argentina has been estimated as 28 Mha [198]. The livestock industry has contracted from 8 Mha in 1999 to 5.1 Mha in 2008 [195].

During the main expansion period (1996–2004) in soybean production the new areas (from 6.1 to 13.3 Mha) came from four main sources; (i) conversion of cropland growing wheat, corn, sunflower and sorghum (25%); (ii) conversion of areas growing other crops (rice, cotton, oats, beans) (7%); (iii) conversion of former pastures and hay fields (27%); and (iv) conversion of wild lands, including forests and savannahs (41%), causing loss of biodiversity [199]. At the same time, the area cultivated for other crops decreased from 18.8 Mha to 13.2 Mha [93]. In the 2000–2004 period soybean production has displaced some 4.6 Mha of land dedicated to other production systems such as dairy, fruit trees, horticulture, cattle, and grain [200]. The expansion of GM soy has generated strong pressure on 'marginal' and non-arable areas (pastures, bush lands, savannahs, forests), previously considered unsuitable for soy cultivation due to heavy weed infestations [44]. The current agricultural practice in Argentina is highly advanced, and more so than in case of subsistence farming in parts of Brazil.

Since 2001, agricultural area expansion has occurred primarily in the north, where new cropland has largely replaced natural vegetation, with relatively slight displacement of pasture and cattle. Growth has occurred at the expense of the Chaco bush savannahs and Yungas subtropical forests [201]. Most future expansion of soy production is expected to occur in the Chaco region. The expansion of mechanised soy farming has been the most important driver for deforestation in the past.

Fig. 3 shows the soybean oil production in Argentina, approximately 7 Mt in 2010. The average soy yields in Argentina have increased from 2275 kg/ha in 1991 to 2905 kg/ha in 2010 despite the fact that meanwhile vast areas of more marginal land (yield depressing) have been incorporated into crop production (Fig. 4). An average yield of 2630 kg/ha/yr was reached in 2001/2002 in

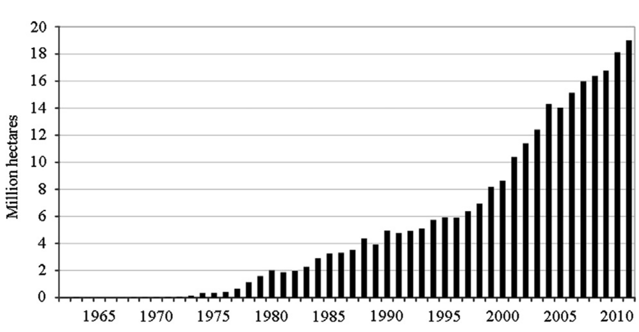


Fig. 2. Soybean area (Mha) harvested in Argentina.
Source: *FAOSTAT*.

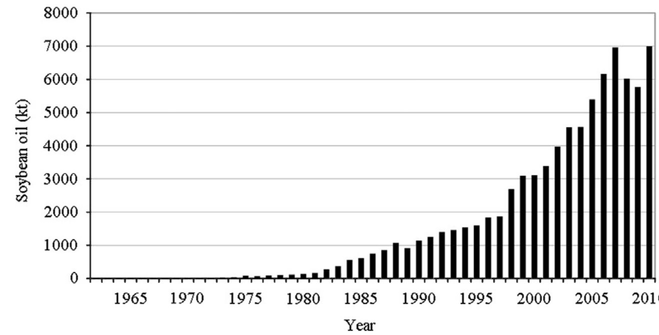


Fig. 3. Soybean oil production in Argentina (kt).
Source: FAOSTAT.

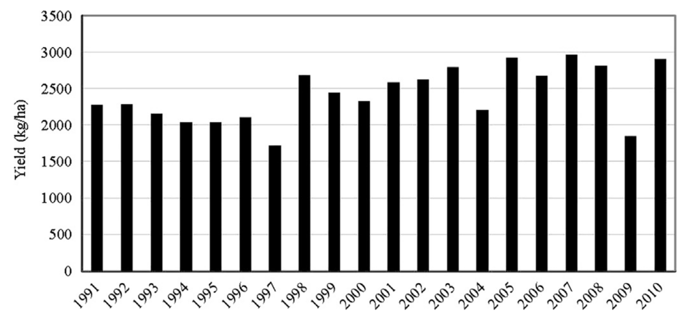


Fig. 4. Soybean yields (kg/ha) in Argentina.
Source: FAOSTAT.

conditions of about 25% soybean area cultivated in a two-crop regime (typically wheat and soybeans), 70% in a no-tillage cropping system using transgenic varieties (RR), and 30% in conventional cropping [202]. No N fertiliser was given as reliance for N supply was put totally on BNF. The current higher yields are due to better genetic materials, increased use of agrochemicals (fertilisers, pesticides), improved weed control, less soil corrosion, improved planting operations and better agricultural technologies. For comparison, average yield in USA (2012/2013 forecast) – mostly corn-soybean rotation – is 2.95 t/ha; other producers (Brazil, Paraguay, Canada, Uruguay and China) average 2.2 t/ha. The agroclimatic conditions in many parts of Argentina are similar to the United States. Precision agriculture is prominent and Argentina is second after US in yield monitoring.

Argentina is in the forefront in the introduction of innovative technologies to farmers. The country is developing sound agricultural practices using no-tilling (avoids soil corrosion), crop rotation (diversifies production risk), disease control (more efficient use of pesticides) and rational use of crop nutrition and fertilisation. First-class soybean is grown between October/November (sowing) and April /May (harvesting), corresponding to the optimal growing period for soybean in Argentina. The soybean cycle lasts for 6 months, and the land is then left and set aside during the winter (crop succession of set-aside land-soybean). Second-class soybean is grown between December (sowing) and April/May (harvesting), after wheat (crop succession wheat-soybean), using soybeans of shorter growing cycle. Wheat is grown between June/July and December (harvesting), when soybean is sowed. This allows two crops per year. As first-class soybean is grown in the optimal period, higher yields are obtained. Both first- and second-class soybeans are grown in monoculture as well as in rotation with corn or sunflower. The area planted with soybeans as first/second crop in Argentina has increased from 4.1/1.9 Mha in 1996 to 11.7/4.25 Mha in 2007 [22]. The distribution of typical production systems, namely first- and second-class soybean in reduced tillage (FCRT and SCRT) and first- and second-class soybean in

conventional tillage (FCCT and SCCT), has been reported as 49.3%, 30.6%, 14.7%, and 5.4%, respectively, with an average soybean yield of 2591 kg/ha [203].

Previous crop management has an impact on the subsequent soybean culture, *cfr*. Sections 2.1 and 3.1. Second-class soybean, cultivated after wheat, is not additionally fertilised as it uses the residual N from the wheat fertilisation. A direct consequence of soy monoculture has been deterioration of the physico-chemical characteristics of the soil. Simultaneously, the indiscriminate and widespread use of insecticides has promoted diseases specific to the monoculture.

Argentina is a referent country in conservation agriculture. No-till was adopted rapidly in Argentina both for soybeans and other crops when transgenic soybean crops with glyphosate tolerance (GT) were introduced in 1996. The NT system, which shortens the time required between the wheat harvest and soybean planting, allows the use of short-cycle soybean varieties as second crops and double cropping wheat-soybeans where this was previously impossible, *e.g.* in areas with lower rainfall. The soybean crop uses no-tillage most prevalently, with 75% of first-crop soybean area and 83% of the second-crop soybean area planted with this technology in 2007; the area under NT cropping reached 88% in 2010 [204].

Zero-tillage has been claimed to have improved soil fertility in the Argentine pampean region [205]. Coupling of zero-till with GT soybeans modifies the crop's interaction with the soil moderating the impact of cultivation, while the use of glyphosate has reduced the negative environmental impact of previously used, more toxic herbicides (such as atrazine). Even with the increased use of fertilisers and agrochemicals, the use of these products (per hectare of arable land) is still far below that of some other countries (*e.g.* China, USA, Brazil). While the total fertiliser use (N, P_2O_5, K_2O; 2006) in Brazil (2297, 3149, 3460 kt) is much lower than in USA (11,970; 4147; 4657 kt), but not per hectare of arable land (*cf*. Fig. 9a), fertiliser consumption (in percentage of total South American use, 2005) is much lower in Argentina (1%) than in Brazil (76%) [135]. On the other hand, fertiliser use efficiency in Argentina is higher than in Brazil and USA (*cf*. Fig. 9b). As farmers are relying increasingly on a single planting system (no-till), a single crop (monoculture) and a single herbicide (glyphosate) soil fertility declines and the need for fertiliser use increases substantially [93]. The energy balance for direct sowing is better than for conventional tillage farming [196].

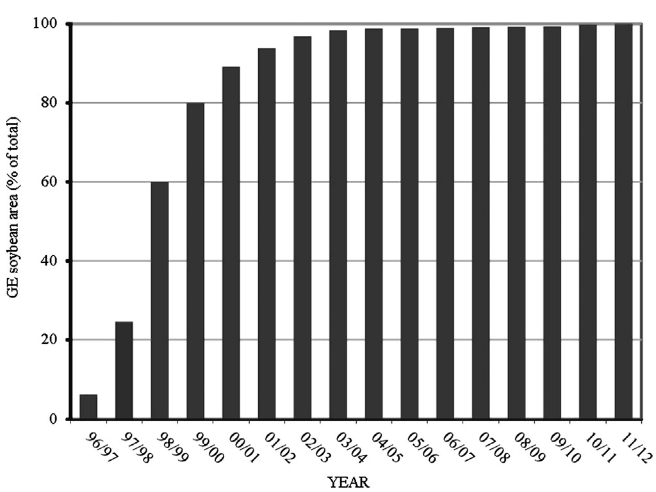


Fig. 5. Evolution of GE soybean area (percent) in Argentina by year.
Source: Argenbio.

Argentina has been a leader in the adoption of biotechnology and is the third largest producer of biotech crops (15% of global production) after the United States and Brazil. Fig. 5 shows that the GE soybean area in Argentina has increased rapidly from 6% in 1996/1997 to about 99% by 2002; *cfr*. only 75% in USA (2002). At present almost all soybean area (18.8 Mha in 2011/2012) is planted with (three) biotech seed varieties (Table 15). Biotechnology is expected to improve yields and nutritional value of crops while decreasing the input of chemical pesticides. These expectations have not yet come true. Roundup Ready® soy has not improved yields in Argentina [206], as opposed to US experience (*cfr*. Section 4), and pesticide use is steadily increasing. Argentine consumers are hesitant about supporting the technology.

The first generation of Monsanto's technology (the so-called 40-3-2 event) has facilitated the incorporation of double crop soybeans (allowing soybeans to be planted following wheat harvest) in many areas where only one crop was planted before the availability of the biotech varieties. The combination of no-tillage systems and transgenic RR soybeans with glyphosate herbicide is at the origin of the phenomenal growth of the soybean industry in Argentina as from the mid 1990s. The Argentine Seed Law allows producers to successively use seeds on their farm, *i.e.* pay royalties only on the original purchase of biotech seeds. By private agreement with Monsanto Argentine farmers representing 11 Mha (or 60.7% of total soy area) will have access to new soybean varieties (Roundup Ready 2Y and Roundup Ready 2YBt) – with royalty payment – as from the next crop season (2012/2013) [207]. The BtxRR2 event is resistant to herbicides *and* insects. Monsanto holds a local patent for this event. Argentine researchers (Bioceres; Rosario, SFE) have recently isolated the drought tolerance gene from sunflower, and have inserted it in varieties of soybean, wheat and corn, obtaining 15–100% higher yields than regular.

Although Argentina has further potential to increase its agricultural output, many studies caution about the way agriculture has expanded since 1995 and question the sustainability of some of the current Argentine agricultural production methods [14,194,200,208].

In recent years, cultivation of soybean has spread to regions of Argentina in which irrigation is necessary for matching the water requirements of crops. Water stress in rainfed cultivation implies a reduction in productivity (typically 14%) [209]. Irrigation allows early crop sowing. The water footprint (WF) of soybean cultivation with no-till sowing in Argentina (Córdoba province) is 2440 m^3/t for the non-irrigated system and 5% higher for the irrigated system; yields are 2.8 and 3.2 t/ha, respectively. The water use

Table 15
Soybean biotech crops approved in Argentina.

Trait category	Event	Application	Resolution
Glyphosate herbicide tolerant	GTS-40-3-2	Nidera S.A.	1996
Glufosinate ammonium tolerant	A2704-12	Bayer CropScience	2011
Glufosinate ammonium tolerant	A5547-127	Bayer CropScience	2011
Herbicide-tolerant, insect tolerant	MON87701 × MON89788 (Intacta RR2 PRO)	Monsanto	2012

After Ref. [207].

efficiency (WUE) level of soybean is 4.39 mg/g, as compared to 10.77 mg/g for maize [210].

The main aspects of the Argentinean agrarian model are expansion, integration and internationalisation of soybean production and commercialisation, to the detriment of alternative farming models. The average Argentinean farm size is quite large: 360 ha in 2000 and 530 ha in 2002; *cf*. average US soybean farm of 92 ha. In Northern Argentina the average soy farm size is around 1 kha. Already in 1992 Argentinean farms of less than 200 ha were deemed to be non-competitive in global markets. Small and medium size farms have winded up rapidly: between 1988 and 2002 about 80,000–100,000 small farms disappeared. Planting consortiums now produce in very big extensions (leased) of 10 kha. In Argentina, more than 50% of cultivated land is leased. In large agricultural farms soy production is highly mechanised and direct seeding is often utilised. Large plants make up 80% of total production.

Soy production in Argentina has benefitted from the economy of scale (large-scale farming) with low costs of land and labour, comparative advantages in terms of freight, relatively high natural fertility of its soil, a climate well suited for soybean cultivation, relatively few serious pest problems (other than weeds), the highest daily crushing capacity in modern and technologically advanced milling plants, and technical innovations (no-till farming, GMO crops), which all contribute in reducing energy consumption, environmental impacts and production costs.

The Argentine soybean sector is largely controlled by five multinationals [208]. The soybean chain is the main export commodity of Argentina. The country is a top exporter of soybean oil (4.6 Mt), and soybean meal (27.6 Mt), with 48.0% and 47.3% of the world's export market in 2010/2011, respectively, and the third-largest exporter of soybeans (13% of total exports). For all three commodities Argentina ranks third among all producers, with almost one-fifth of the world output (Table 4) [30]. About 85–90% of soybeans grown in Argentina are exported to world markets (in particular China and Thailand) for animal protein feed supplements and vegetable oil. Soybean meal exports to EU-27 amounted to 13.2 Mt (2011/2012). The share of soybeans production crushed in Argentina is almost 75% (2008). Rosario (SFE) is the main port for export of Argentinean soybeans (75%), soybean meal (97%) and soybean oil (97%). An important logistical advantage of Argentina is that the majority of its soybean crushing plants are in proximity of the Paraná river. Whereas the infrastructure (export route) for agricultural products is excellent, inland transport conditions for transportation to port facilities are still relatively poor.

The Argentine soybean chain differs from Brazil and the United States. Soybeans are barely consumed on the domestic market (5% out of 45.5 Mt in 2007) and there is also little domestic demand for soybean meal. Increased soybean production and crushing imply an increase in vegetable oil production (7.4 Mt in 2010/2011). In order to meet the biodiesel industry needs the industrial domestic consumption of soybean oil has recently increased by 300 kt to 2.2 Mt [211]. In 2012 Argentina utilised about 40% of its SBO production for biodiesel. This compares to a domestic consumption of 80% of soybean oil production in the United States and 75% in Brazil. Soybean oil and soy biodiesel are both mainly exported, with export taxes of 32% and 16.6%, respectively.

6.1. Biofuels policy in Argentina

Argentina is a net importer of fuel (gas, diesel, gasoline). Being a large exporter of grains, sugar and vegetable oil, it seems reasonable to convert part of these exports into energy and reduce fuel imports. Law 26.093 (April 2006) involves a regulatory and promotion regime for the sustainable production and consumption of biofuels. The main objectives of the Argentinean regulatory framework concerning biofuels are: (i) diversification of the energy supply; (ii) creation of a more environmentally friendly energy matrix; and (iii) promotion of the development of rural areas, particularly small and medium agricultural producers. Under Law 26.190 of 2006, named National Support for the Use of Renewable Energy Sources, and its regulatory framework established in 2009, the government has created the Renewable Generation (Genren) program, with impacts on biodiesel. Its objectives include reduction of CO_2 and other GHG emissions.

Goals of the Argentine National Bioenergy Program (NBP), coordinated by INTA (Instituto Nacional de Tecnología Agropecuária/National Institute of Agricultural Technology), are to ensure the supply of sources of bioenergy in support of sustainable development, national energy security, the reduction of poverty, the attenuation of climate change and environmental equilibrium. At a technical level, objectives include (i) identification of the potential of different energy crops; (ii) development of non-traditional crops with energy potential; and (iii) development of second-generation biofuels through the identification of cellulose-degrading enzymes. Research is primarily focused on feedstocks which can be produced in areas not suited for crop production and which do not compete with food production. Several programmes focus on jatropha, algae, castor bean, canola, sweet sorghum and miscanthus.

The Argentine situation presents great opportunities for the biodiesel industry and the country has created a domestic biodiesel market in 2007 [212]. Argentina's interest in biodiesel derives from security of energy supply, diversification of energy carriers, autoconsumption by farmers and export markets overseas. At variance to the EU, the key driver of a domestic biodiesel market in Argentina is therefore not reduction of GHG emissions but rather economic development. Argentine law allows tax exemptions and has introduced a 5% blending requirement of biofuels in conventional fuels for transportation from the beginning of 2010. This translates into 650 ML of biodiesel and 250 ML of bioethanol. Participation of SMEs in the emerging industry is key to a socially sustainable industry. Law 26.093 lacks transparency. Sustainability was left ill-defined. Moreover, although the law aims to prioritise production for the domestic market by small producers in non-traditional production areas, Argentinean soy biodiesel production for both the domestic and export markets is now firmly in the hands of large, vertically integrated producers, consolidating the agro-export model [213]. The strong industrial lobby (within the vegetable oil and petrol companies) favours very large-scale biodiesel production, where the role of small and medium enterprises (SMEs) is limited. Argentina's soy biodiesel is very cost competitive internationally (and almost price competitive with petrodiesel), not in the least place by the economy of scale [82]. However, Argentina cannot become diesel self-sufficient (consumption of 14.4 Mt in 2010 of which 3.8 Mt imported) through soybean-derived biodiesel unless the cultivation area is extended significantly, which is unsustainable [214].

Argentina has rapidly become one of the world's top producers of biodiesel (projected at 2.8 BL by 2013), mainly for export since 2007 (1.5 BL by 2013) [215]. The mandatory B5 blending requires 3.6 Mt of soybeans and 1.5 Mha dedicated soybean area. This mandate (meanwhile raised to B7 in 2011 and moving to B10 by 2015) for the Argentinean transport fuel matrix requires that 8.3% of the current soybean cultivation area would have to be devoted in 2010. In case the Argentine blending mandate will be raised to B10 it would be one of the highest in the world.

Argentina's biodiesel production capacity has reached 3.95 Mt (2011), mainly located in Santa Fe province (80%), and is projected at 4.65 and 5.27 Mt by the end of 2013 and 2015, respectively [215], *cf*. Fig. 6. This impressive biodiesel plant capacity would

require approximately 50% of the production of soy current plantings and would sustain about 35% of the country's diesel needs. The production potential for Argentine soy biodiesel production is high in view of the abundant availability of soybean oil for export and low production costs.

Biodiesel production scales in Argentina are commonly distinguished in

- Individual producer scale (< 5 kt/yr), mainly for self-consumption, with low standards of product quality, environmental impacts and safety.
- Cooperative or regional scale (5–33 kt/yr).
- Large scale (> 33 kt/yr), often with integrated seed crushing.

The total installed nameplate capacity (2011) consists of 22 large plants (164 kt on average; range from 36 to 500 kt); 17 medium plants (20 kt on average; range from 6 to 30 kt); and 1 small plant (4 kt). Small biodiesel plants (< 5 kt/yr) account for only 0.1% of total production, medium-scale plants (up to 33 kt/yr) for 8.6%, and large-scale plants for the vast majority of production (91.4%). It has been recommended that production on a small scale should not be promoted at all (lower efficiency, lack of quality and of environmental control on processes) [82]. Unlike Brazil, the focus in Argentina lies mainly on (very) large-scale production (160 kt/yr on average), derived exclusively from soybean oil despite the fact that the country is also a main producer of SNO, RSO, SFO and PNO. However, none of these alternative feedstocks can currently commercially replace soybean oil in volume and cost. Other potential feedstocks are TLW/UCO (from beef industry/restaurants) and jatropha (North-West Argentina). Benefits of the Argentine soy biodiesel production model comprise:

- No-till production with the presence of a permanent soil cover (crops or crop residues).
- Hi-tech crushing plants at less than 300 km from soybean production sites.
- Biodiesel plants connected with the San Lorenzo export port through pipelines (reducing GHG emission of inland transport).

One of the key factors of the rapid development of the local biodiesel industry (see Fig. 6) has been the differential export tax on biodiesel *vs.* soybean oil. Vegetable oil companies have strong incentives for large-scale production of biodiesel for which export tax is around 16% lower than for vegetable oil. Argentina levies retentions to exports as state tax revenues and to maintain low internal food prices. The export tax is lower for processed products (biodiesel *vs.* vegetable oil *vs.* beans). This tax regime guarantees a low-cost supply of feedstock for biodiesel production and gives greater competitiveness in the internal market. Sliding biodiesel export taxes (17–24%), depending on soybean prices, introduced in September 2012, have created high uncertainty for producers. Most large plants are vertically integrated to their existing modern crushing facilities (*e.g.* Vicentin, Renova, Ecofuel, LDC Argentina and Rio Molinos de la Plata), and have their own ports. Meal is the main product (primarily for export) while soybean oil is considered as a by-product. Fig. 7 shows the development of crushing capacity in Argentina. Current mega projects include Enarsa's Timbuès (SFE) crushing (3 Mt/yr) annex biodiesel production plant which will use only soy oil as feedstock. Large-scale production of biodiesel can affect the market for soy meal.

The average use of Argentine biodiesel nameplate capacity is around 55%, *cf.* 40% in Europe. Argentina's export markets vary with time: USA (81.7%, 2008), The Netherlands (52.9%, 2009) and Spain (40.6%, 2010; 51.2%, 2011) [216]. In 2008 Argentine biodiesel exports to the US were favoured by the splash-and-dash subsidy and GSP benefit (duty free regime) in the US market. In 2010 the EU reduced the Argentine exports of biofuels. In 2011 Argentinean biodiesel production (2.40 Mt), domestic consumption (0.60 Mt) and export (1.80 Mt, forecast) all set records. In 2011, out of the 1.6 Mt biodiesel consumption in Spain, 720 kt originated from imports from Argentina. Closing of the Spanish market for biodiesel from outside the EU (following nationalisation of the majority Repsol-owned YPK), Argentina's top export destination, requires redirection of Argentina's biodiesel market (*e.g.* to Germany and The Netherlands). Implementation of sustainability systems in the EU are unlikely to negatively affect the volume of imports from Argentina which has made arrangements to certify its production under the rules applicable in the EU. However, exports to EU-27 could drop significantly on the basis of Community legislation restricting the overall use of conventional (first-generation) biodiesel [217]. Other export destinations are South American countries (Peru, Colombia). The US market is again an export goal as Argentine biodiesel is highly competitive and qualifies as biomass-based diesel. As a result of the Spanish action overall Argentine biodiesel exports 2013 are expected at the lowest level since 2010 (Table 16). However, domestic consumption in 2013 will continue to grow as a result of larger purchases by electricity companies and a growing fuel market despite uncertainty on the prospected increase in mandate mix from 7% to 10%.

The Argentine biofuels sector continues to expand as a result of its strong competitiveness, vast feedstocks, excellent processing infrastructure and favourable policies, taking advantage of an important domestic advantage of SBO over producers elsewhere

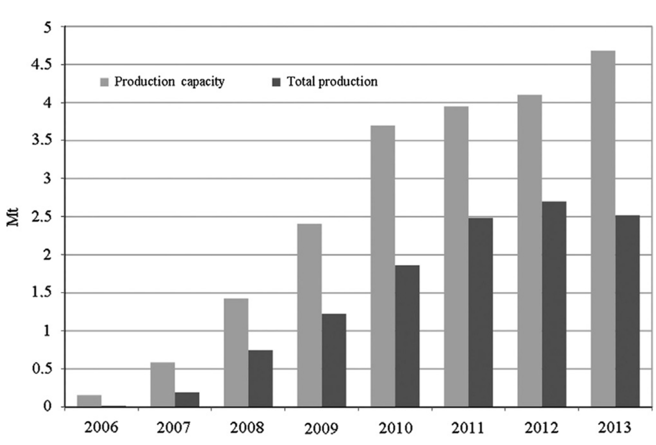


Fig. 6. Biodiesel production capacity and total production in Argentina (2013 forecast).
Source: Argentine Renewable Energies Chamber.

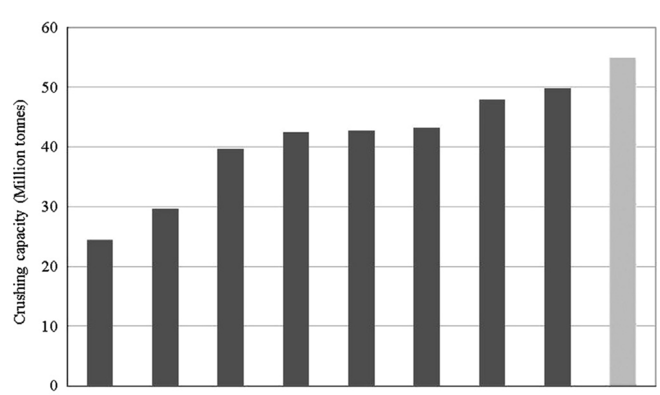


Fig. 7. Development of crushing capacity in Argentina (2012 forecast).
Source: Molinos Research Department.

Table 16
Argentine internal demand and remaining export capacity for soy biodiesel (Mt/yr).

	2010	2011	2012	2013
Production	1.80	2.40	2.75	2.35[a]
Domestic demand	0.50	0.60	0.75	1.00[a]
Export capacity	1.30	1.80	2.00	1.35[a]

[a] Forecast.

Table 17
National surface allocated to soybeans, percentage compared to total arable land, seed yield and oil yield for various European countries.[a]

Country	Surface[a] (kh)	Arable land (%)	Seed yield[a] (kg/h)	Oil yield[b] (kg/h)
Croatia	49.01	3.93	2588	466
France	41.94	0.14	2657	478
Hungary	33.32	0.57	2248	405
Italy	143.76	1.01	3335	600
Romania	95.89	0.70	1942	350
Russian fed.	786.47	0.36	1062	191
Serbia	127.02	3.14	2569	462

[a] Based or extraction yield of 18%.
[b] FAOSTAT data, average 5 years 2005–2009.

(32% below international market price). The financial prospects of the Argentine biodiesel industry are very favourable, as opposed to those of Northern hemisphere producers [82]. By vertical integration from soy farming to crushing and biodiesel production, the Argentinean producers are highly competitive on the world market. However, biodiesel business is not only an economic concern. Environmental and social sustainability standards are equally needed (*cf.* Section 10.1.2).

7. European soybean complex

As the agricultural area in many European countries (*e.g.* Switzerland) is a constrained resource and not even sufficient for food production for the whole population, rendering food imports necessary, such countries are unlikely to ever become producers of energy crops. An overall increase in the use of biofuels is then only possible with the import of bioenergy products (*cf.* refs. [105,109]). Given the constraints on European agriculture characterised by an overall slightly decreasing area [28], excessive fertiliser use and diminishing rate of increase in yield [218], long-term options for cultivation of energy crops are most likely to be extra-European (with greater GWP and total environmental impact), apart from still untapped areas in Southeastern Europe (Romania, Ukraine). Europe is climatically better suited to cereals production than oilseeds with EU importing almost 50% of its oilseed requirements. Oilseed production on unsuitable EU land (*e.g.* Baltic countries) is hardly an option.

Total EU-27 oilseeds production (2011/2012) is around 29.4 Mt (of which 20.82 Mt of rapeseed, 7.00 Mt sunflower seeds, and 1.16 Mt soybeans) cultivated at a total oilseeds area of 11.5 Mha [39]. The EU-27 soybean production on 416 kha (forecast), quite small compared to the total demand and relative to imports (12.2 Mt), consists mainly of non-biotech soybeans for food use. Soybean is grown in some 20 European countries with the Russian Federation being the main producer but with low seed and oil yields; Italy reports the highest yields (Table 17). The leading soybean producer in EU-27, with 35% of production, is Italy, with Romania and France ranking next. Spain, Germany, Italy and the Benelux countries account for roughly 80% of the EU-27 soybean crush of 12.0 Mt. The largest users of soybean meal (32 Mt, 2011/2012) are the major producers of livestock and poultry (Germany, Spain and France).

There is no intervention buying, export subsidy or other market support for oilseeds in the EU. EU countries are increasingly applying RED-related sustainability criteria and certification (*cf.* Section 9.4). This temporarily upsets trade flows for oilseeds. Imported soybeans, which are generally not yet RED compliant, are currently being refined in Germany, and the resulting oil is exported to countries that have not yet implemented the RED. Europe is also increasingly importing palm oil for hydrotreating (as HVO diesel; 1290 ML in 2012) in commercial plants in Finland, The Netherlands and Italy. A few other advanced biofuel plants (based on BTL, DME, methanol) are operational in EU 2012 at demo to commercial scale [25].

7.1. Soy biodiesel in Europe

The EU is the world's largest regional biodiesel producer, consumer, and importer. Table 18 shows the growth in EU biodiesel consumption. EU-27 biodiesel consumption for transport amounted to 10,690 ktoe (2011) out of a total EU biofuel transport consumption of about 14 Mtoe; the bioethanol share is about 21.1%. However, Europe's biofuel consumption growth is waning from 41.7% in 2007/2008 to only 3.0% in 2010/2011. The EU share of world total biodiesel has also dropped, from 53% in 2010 to 43% in 2011. In 2011 about 20% of the domestic use of biofuels was imported from outside the EU [25].

Despite increased mandates and the slight increase in biodiesel consumption, EU-27 biodiesel production dropped from 9.57 Mt (2010) to 8.80 Mt (2011). Nevertheless, EU biodiesel production forecast 2012 stands at 10.5 Mt (in 256 biodiesel plants with a total installed capacity of 22.25 Mt) with imports of 2.4 Mt or 22.5% [219]. Imports are expected to drop to 17.6% in 2013 [25]. The French Diester Industrie is the leading European and global biodiesel producer (2.1 Mt in 2011). Plant capacity is presently highly underutilised (< 40% in 2012) with a downward trend since 2006 (46%). Capacity utilisation varies greatly per EU member state (from 2% in Estonia to 98% in Denmark, 2011). Biofuel mandates form a guaranteed minimum level of demand which determines capacity utilisation. EU biodiesel consumption is expected to be 17.3 Mtoe by 2017 according to the national renewable energy plans of the member states. However, the first-generation biodiesel share has been limited and will probably not exceed the 2011 level [217].

Out of the total EU 2008 biodiesel consumption 83% was EU produced and 17% had an extra-EU origin [220]. While the EU produces most of its biodiesel demand within the EU, a significant portion (42%) of the feedstock for that biodiesel is being imported. In Europe, the cost of the feedstock typically employed in biodiesel production (RSO) is roughly 25% higher than that of SBO in the US. In 2012 feedstock used for EU biodiesel production consisted of 10.8% soybean oil (1.14 Mt). The usefulness of soy biodiesel is questionable in the colder Northern European climates but would give little problems in Southern Europe. The vast majority of soy biodiesel is used in Spain, Portugal, France and Italy. French biodiesel (2011) contained 28% soybean methyl ester [26]. The use of soybean is limited by the EU biodiesel standard EN 14214 (the most demanding in the world) as soy biodiesel does not comply with the prescribed iodine value (max 120 g I_2/hg). However, it is possible to meet the standard by using a feedstock mix with rapeseed oil. Total soy biodiesel consumption in EU 2008 amounted to 1266 ktoe (55% EU produced, 45% extra-EU origin). Of the 691 ktoe biodiesel produced from soybean oil in EU 2008 only 82 ktoe was produced from EU soybeans. EU soybean-based

Table 18
EU road transport biofuels.

	2006	2007	2008	2009	2010	2011	2012
Biodiesel consumption (ktoe)	4145	5848	7516	8998	10,019	10,690	10,982
Bioethanol share (%)	17.5	17.0	19.2	20.4	20.7	21.1	21.8
Actual blending (%)	1.68	2.32	3.11	3.85	4.26	4.53	4.65
Target (%)[a]	2.75	3.50	4.25	5.00	5.75	–	–

After Ref. [219].
[a] According to EU Directive 2003/30/EC.

biodiesel stemmed especially from soybeans from USA (528 ktoe biodiesel eq.), Brazil (342 ktoe) and Argentina (238 ktoe) [220]. The introduction of countervailing and anti-dumping duties on US exports of biodiesel to the EU by the EC in March 2009 has dramatically reduced EU biodiesel imports from the United States. At the same time, soy biodiesel imports from Argentina and palm biodiesel from the IndoMalay region have strongly increased. Total EU imports are still slowly increasing (now exceeding 2 Mt/yr).

Biodiesel crops produced in the EU are exclusively food crops. The total gross land use associated with EU biofuel consumption in 2008 has been estimated as 7 Mha (3.6 Mha in EU, 3.3 Mha extra-EU). These 7 Mha represent 4.4% of the total EU utilised agricultural area (159 Mha in 2010). In 2010 the biofuel market coverage in EU-27 was 4.26% (target 5.75% on energy basis), *cf.* Table 18, which was not even all being reached by sustainable methods. It is difficult to estimate the arable land needed to reach the RED targets because of the vast differences in yields between different types of land. It has been stated that the *extra* crops needed to achieve the required increase in biodiesel production (5.75%) would replace 27% of EU 2012 cereals production or roughly 19% of arable land capacity including set-asides [221], which is unsustainable. The EU Common Agricultural Policy (CAP) does restrict the conversion of pastureland to cropland, but pastureland is not used to produce biofuels.

8. Soybean crop in China

China's 2011/2012 forecast of soybean production is 14.4 Mt with imports of 58 Mt, mainly from USA (45%), Brazil (36%) and Argentina (16%) [222]. China, which did not import soybeans until 1997, has now become the global import leader for soybeans. Soybean imports have increased steadily from 3.95 Mt in 1999 due to continuing growth in protein meal demands by China's animal and aquaculture sectors, vegetable oil consumption and stagnant domestic production. Domestic production on a planted area of 8.7 Mha (average yield of only 1.7 t/ha) is decreasing as producers are shifting area to more profitable crops. Soybean planted area is mainly located in the Northeast (Heilongjiang province, 4.4 Mha) and Yellow River region (Shandong, Henan and Hebei provinces) as well as in southern provinces (Anhui, Jiangsu). Domestic soybean production is oriented towards 'non-GMO, high protein and food use'. China is a biotech-free soybean producer. Most of the soybean production is consumed locally in food products.

China has experienced intense land-use changes for decades with conversion of forests and grassland to (low-productivity) cropland, which still resulted in a net loss of cultivated land of almost 5 Mha from 1991 to 2001 [223]. Any prospective biofuel increase in China will be associated with large GHG emissions from DLUC.

Inadequate farming practices such as deep tillage (30 to 60 cm) and close cropping with overdoses of fertilisers – and high (human) energy expenditure – were once propagated during the Great Leap Forward (1958–1962). Today's Chinese soybean farming with low yields (35% lower than in Argentina), lack of crop rotation and poor efficiency, is characterised by low international competitiveness. PRC farmers still utilise high fertiliser application rates in agricultural production, where half of the N fertiliser is made from coal feedstock. The Chinese energy mix is dominated by coal. Total material input cost share for soybean production in China is as follows: seeds 35%, fertilisers 46%, organic manure 3%, pesticides 14%, and irrigation 2%. The practice of Chinese farmers of applying a high dose of N fertilisers (75 kg N/ha) in a single dressing before the flowering stage seriously reduces symbiotic N_2 fixation and is an inefficient fertiliser strategy for maximising grain yield and economic return [34]. Gan et al. have reported the effects of N management on growth, N_2 fixation and yield of Chinese soybean [34]. Also the Chinese practice of removing crop residues from the field should be discontinued.

The oilseed industry in China faces limited arable resources, organic and technical deficiencies, competition with higher profit crops (grain, corn, rice), and government policies that favour grains over oilseeds, but it profits from an excess of crushing capacity (> 100 Mt in 2011) and growth for oilseed by-products (meal). China crushes about 70% of its total soybean supply. China is the largest market for soybean oil, because of high levels of demand for cooking oil which cannot be met by domestic production. Soybean oil is the main vegetable oil produced in China (55% of total production), followed by RSO (26%), PNO (11%) and CSO (6%) in 2011/2012. Soybean oil production (2011/2012) stands at 11 Mt, with imports of 1.7 Mt. Argentina is the largest soybean oil supplier to China. China is the world's largest importer of oilseeds (PMO, RSO and SBO), and is likely to remain the largest global consumer.

8.1. Soy biodiesel in China

PR China is the world's second largest consumer of transportation fuels; 35% of China's oil consumption is diesel. China's diesel consumption in 2011 was 3.5 Mb/d, of which 70% on account of the transportation sector. With its coal dominant and highly polluting energy structure, China is actively developing bioenergy technology, in particular biogas (target of 44 billion m^3 by 2020). China has been promoting biofuel production since 2002, mainly bioethanol [224]. With renewable energy legislation in place in 2006, the country aims at a renewable energy share of 15% and a biofuels mandate of 10% by 2020. To date nine Chinese provinces have 10% ethanol blend (E10) requirements. Biodiesel production (of unstable quality) and commercialisation are still very limited, reportedly 38–60 kt (2004), 100 kt (2007) [225] and 250 kt (2008). Reliable data for China's biodiesel production are not available. The target set in the 'Medium- and Long-Term Development Plan for Renewable Energy in China' (2007) is 2 Mt by 2020 (corresponding to the used cooking oil potential). There are currently only a few small-scale biodiesel plants in China, using UCO as feedstock [226,227]. Using process energy for biodiesel production derived from hard coal leads to high GHG emissions in the biomass conversion process. Such emissions are significantly reduced by

using process energy generated from renewable sources or from by-products of the process chain.

The market for biodiesel is limited to local distribution, direct sale and purchase, due to the low and irregular output and limited market access. There are no government subsidies for biodiesel production. China is committed to using non-food feedstocks (UCO, TLW, jatropha) [228] but the biggest biodiesel producers also adopt rapeseed and soybean oil as raw materials. Most biodiesel is used in agricultural machines and fishing boats because use as a vehicle fuel is forbidden. In case of a B5 mandate China would need 6.3 Mt/yr biodiesel (based on 2011 consumption). For the developing biodiesel industry in China, *cf.* Ref. [227].

Given its limited agricultural potential (122 Mha or 0.081 ha/inhabitant), far below the US potential (0.49 ha/inhabitant), China is unlikely to be able to grow energy crops to any large extent. Biodiesel forests based on potential shrubs and trees, including jatropha and Chinese pistache, are under development by the Chinese State Forestry Administration (SFA). Chinese biodiesel prospects are long term. A national biodiesel quality standard is urgently needed.

9. Discussion

9.1. Sustainability

Sustainability issues have become prominent over the last years. Sustainable development (SD) meets the needs of the present without compromising the ability of future generations to meet their own needs [229]. Sustainable production and consumption are vital for the long-term perspective of global industry and trade. Sustainability leads to limitations regarding the use of renewable resources.

The term sustainable has many meanings. Sustainable use of biomass can be continued indefinitely without an increase in negative impact due to pollution while maintaining natural resources and beneficial functions of living nature relevant to mankind over millions of years, the common lifespan of mammalian species [230]. Agriculture is in a critical role to sustainably support the needs of the growing global population with minimal impact on the earth's natural resources. Chemistry is fundamental to understanding the problems humanity is facing, and can provide innovative solutions for sustainable biofuels [231], *cfr.* also Table 19.

Agriculture makes use of different definitions of sustainable production methods: Good Agricultural Practice (GAP), integrated or organic agriculture [232]. The main objectives of sustainable agriculture are production (crop yields) and conservation using environmentally sound land management, care for environmental health, social responsibility and economic profitability. Sustainable, climate-friendly agriculture is highly wanted.

Table 19
Sustainable product design.
Source: www.rsc.org/roadmap.

Environmental impact
• Improved life-cycle assessment (LCA) tools and metrics
• Standardisation of LCA methods and data gathering
• Method to assess recycled materials
• Improved understanding of ecotoxicity
• Efficiency in application
Chemistry and chemical engineering
• Structure–property relationships
• Technology for designing biodegradability into finished products
• Green chemistry
• Manufacturing process intensification and optimisation
• Process modelling, analysis and control
• Substitution of toxic substances
• Readily recyclable products
• Improved recovery process

For sustainable biomass-for-energy production the following stocks of natural resources are important: soil, soil organic matter, soil nutrients, fossil fuels and water. Erosion and water usage should not exceed addition to stocks of soil and water and levels of nutrients and organic matter in soils should not decrease [230]. Agriculture accounts for about 75% of current water use [233]. The bioenergy chain should guarantee climate neutrality (from pre-sowing to post-harvesting procedures and use). As global land area for biomass production is a limited resource, boosting biofuels production increases the competition between various end-uses of biomass, such as food, feed, fuel, chemicals, materials, and heat and/or electricity production, but also affects biodiversity, and social and cultural values. Biodiesel's sustainability is usually compromised in case of land-use changes.

The water requirements of biofuels production mainly depend on the type of feedstock and on regional variables such as (micro) climate and geographical characteristics, being feedstock cultivation the most water-intensive of all biofuel production processes. The consumptive water use of soy biodiesel is about 6500 L/L biodiesel [75]. Large-scale expansion of energy crop production will lead to a large increase of evapotranspiration for human uses, which could locally lead to further enhancement of an already stressed water situation. Water availability does not impose a constraint on the assumed level of bioenergy production in countries such as Canada, Brazil and Indonesia. However, other countries (*e.g.* China) are already facing a scarce water situation, which is not improving by large-scale bioenergy feedstock production. USA and Argentina are projected to join the group of countries that withdraw more than 25% of available water. The reason is large pro-capita withdrawals rather than scarce availability [234].

Sufficient mineral nutrients (such as N, P, S, K, Ca and Mg) should be maintained indefinitely by the agricultural practices used. Large deficits in nutrients are expected if no fertilisation is used. Yet, use of virtually non-renewables, such as phosphate ores and fossil fuels, should be minimised. Substitution of mineral fertilisers with organic ones (organic farming) and the use of vegetable oils in diesel engines for agricultural machines and transport (on-farm, produced biofuels) favour sustainability and reduce the dependence on non-renewable energy sources [235,236].

Current initiatives in the US and EU account for the sustainability aspects of biofuel production [237–239]. Levels of volatile carbon compounds and N_2O in the atmosphere should remain unaffected. Irreversible climate changes would be catastrophic. However, the atmospheric CO_2 level (now about 400 ppm) already increases annually with 2 ppm [240]. The increasing use of nitrogen-based fertilisers, N_2 fixation (for cultivation of soybean and other leguminosae) and atmospheric nitrogen deposition on agricultural lands is believed to be largely responsible for the current annual increase of 0.8 ppb yr^{-1} in N_2O atmospheric concentration (323 ppb in 2009) [241].

This paper identifies the major sustainability concerns associated with resource use and the potential environmental and societal consequences of widely deployed commercial-scale soy biodiesel and explores the opportunities for mitigation. Some of the resource use and environmental concerns, as well as mitigation strategies, might affect the economic viability of soy biodiesel. The economic performance of biodiesel depends on factors such as local resource conditions, cost-effective feedstock, technical feasibility, economy of scale, suitable commercialisation methods, incentive policies, *etc.* (all very favourable for Argentina, as

opposed to China). The economics of biodiesel production (in terms of criteria such as business viability, long-term prospectives, reliability of resources, yields) is generally poor. Trade-offs between economic and environmental implications of biodiesel commercialisation are not uncommon, as in case of the Philippines' coconut biodiesel program [242].

The sustainability goals for soy biodiesel are to contribute to energy security and continuity of supply by providing a domestically sourced fuel, to maintain and enhance the natural resource base and environmental quality, to produce an economically viable fuel, and to enhance the quality of life. The main (interdependent) aspects of sustainability of soy biodiesel are environmental, economic and social effects of production and use.

Table 20 lists the potential sustainability concerns for large-scale production of soy biodiesel. Potential sustainability concerns of high importance are EROI, GHG emissions, water use, nutrient supply, and appropriate land resources. All of these key sustainability concerns have to be addressed in an integrative manner and mitigation strategies need to be developed, where necessary. The potential environmental effects listed in Table 20 can be divided into three types:

- Effects that can be minimised or prevented by proper management of soybean cultivation, such as adverse effects of GE soy.
- Potential effects that have not yet been assessed, for example the effects of large-scale soybean cultivation on local climate.
- Effects that need to be assessed for each soybean production pathway, such as effects of potential land conversion or GHG emissions; net GHG emissions.

Sustainability, that is environmental, economic, and social implications of biomass-based products, varies significantly between the products and depends on many factors throughout the product's entire life cycle. Life-cycle analysis (LCA) is a valuable tool for the assessment of environmental sustainability of fuel products (even though not covering all environmental criteria; *cf.* Table 22). The economic and social dimensions of sustainability have so far not been included in LCA. However, these dimensions throughout an entire life cycle of a product can be assessed with tools such as Life-Cycle Costing (LCC) and Life-Cycle Social Assessment (LCSA). In addition, environmental extended input-output modelling offers possibilities to combine all three dimensions of product systems being assessed [243]. Risk analysis can also be integrated with LCA [243].

Measuring the sustainability of biodiesel is not straightforward. Each of the three sustainability aspects (environmental, economic and social) comprises numerous sub-categories which makes setting up of sustainability criteria difficult. This is also reflected in the number and scope of existing initiatives and certification systems (*cfr*. Section 9.4). Further development of the criteria to ensure sustainable production of biofuels is urgently needed.

Sustainability standards should not only apply to soy biodiesel but should ideally be extended to all agricultural commodities. Such standards can be linked to subsidies and tariffs, which may affect international trade (within WTO rules). No commonly agreed-upon voluntary or legally binding international agreement exists yet for sustainable biomass standards. However, the EC is securing sustainable biomass standards for the EU-27 region.

9.2. Sustainability criteria

Sustainability concerns do not only apply to the biofuels sector. Sustainability standards – preferably one uniform internationally applicable standard – should be extended to all types of biomass production. However, as standards cannot easily be generalised for all biomass producing countries, sustainability criteria (SCs) need to be adapted to regional conditions [244]. In order to operationalise sustainability assessments of biomass systems it is essential to identify critical criteria. Formulating such SCs is a considerable challenge as ambiguous and generic criteria, without measurable indicators, are difficult to enforce. Consensus as to the critical indicators of sustainability is slowly developing. ISO/CD 13065 (Sustainability criteria for bioenergy) is a forthcoming international standard (2014) [245].

Various early initiatives have been taken by trade organisations, NGOs (*e.g.* WWF), processors/suppliers/retailers (*e.g.* Unilever, Coop). For instance, Unilever has developed a corporate Sustainable Agriculture Code (SAC) [183] (*cf.* Table 13) and has also expressed its concerns about current biofuel policies [246]. The purpose of the Basel Criteria for Responsible Soy Production, developed by ProForest Consultancy for WWW Switzerland and the Swiss retailer Coop, was to establish guidelines for sustainable,

Table 20
Potential sustainability concerns for large-scale production of soy biodiesel.

Concerns of high importance
- Supply of the key nutrients for soybean growth – nitrogen, phosphorus (fertilisers). Preparation and transport of fossil inputs required to produce necessary nutrients affect EROI and GHG emissions
- Growth of (toxic) agrochemicals use
- Quantity and quality of water needed for cultivation
- Appropriate land area with suitable climate and slope, near water sources (avoiding irrigation)
- Competition between food and non-food uses
- Energy return on investment (EROI > 3).
- GHG emissions over the soy biodiesel life cycle
- Health effects (pesticides)
- Violation of human rights (dispossession)

Concerns of medium importance
- Effects from land-use changes if pasture and rangeland are converted to soybean cultivation. DLUC and ILUC affect the net GHG emissions of soy biodiesel
- Air-quality emissions over the life cycle of soy biodiesel. Emissions from agriculture, processing facilities and tailpipe emissions
- Releases of chemicals (pesticides, nitrates) into soil or surface waters
- Degradation of soil fertility (nutrient depletion)
- Consequences of monoculture
- Effects on terrestrial biodiversity from changing landscape pattern as a result of infrastructure development for soybean cultivation

Concerns of low importance
- Potential adverse effects and unintended consequences of introduction of GE soybeans
- Potential effects of mega soybean farming on micro-climate

ethical and responsible production, transport and storage of soy, and the traceability of soy-derived foods back to the farm [247]. The Basel Criteria, which address issues such as legal compliance, environmental criteria, forest conversion and worker's rights, served as an input to the global roundtable process on sustainable soy (*cf.* Section 9.4). The ProTerra® Standard on social responsibility and environmental sustainability, developed by CERT ID, enlarged that original concept; it is applicable to all agricultural products [248]. The Sustainable Trade Initiative (Initiatief Duurzame Handel, IDH), initiated by the Dutch government, aims at ensuring (amongst others) that by 2015 all soy for food production is sustainable [249].

Concerns about potential negative effects of large-scale biomass production and export have led to the demand for SCs and certification systems that can control biomass trade. Fundamental to effective indicator development is an understanding of the trade-offs in satisfying complicating objectives between society and business. SD indicators concentrate on the environmental, social and economic impact of a product [251–253]. Lewandowski et al. [254] have reported more than 100 social, economic, ecological and general criteria for sustainable biomass trade. Most of the environmental performance indicators of Table 2 are not easily measurable and are therefore not a guidance for decision-makers. Verification and control are necessary. A multi-stakeholder approach is necessary for SC development. Although a wide array of criteria have been developed for sustainability assessment of bioenergy systems, no set is universally accepted [230,239,254,255].

On the basis of a literature review key indicators and SCs have been defined against which these can be assessed for biofuels systems (Table 21). Markevičius et al. [250] have identified 16 environmental, 15 social and 4 economic criteria which have been ranked in Table 22. The most important biofuels sustainability concerns relate to the main possible impacts: GHG and energy balance, soil properties, biodiversity loss, impacts on water and water quality, land-use changes, *etc.* GHG and energy balance are perceived as especially critical. The majority of the 12 most important criteria focus on environmental issues, 4 are social and only 1 is economic. Social criteria ranked rather low. Although being perceived as important, food security ranked only 16th. For the formulation of a certification standard SCs need to be operationalised and measurable.

Sustainability criteria are only of value if they can be implemented. They should conform to internationally accepted norms regarding trade restrictions and discriminatory regulations. It is noticed that not all Dutch 'Cramer Criteria' [239] do comply with EU and WTO regulations [256].

International initiatives, such as the Global Bioenergy Partnership (GBEP), are playing a role in the much needed harmonisation. The mission of GBEP, launched in May 2006 after the 2005 G8 Gleneagles Summit and consisting of a voluntary partnership of 46 developed and developing nations, numerous private sector associations and international agencies, is to promote wider production and use of sustainable biomass and biofuels in particular in the developing world. GBEP aims at reaching consensus on bioenergy sustainability, encouraging integration for greater consistency and reducing duplication. GBEP has proposed a set of 24 technically sound and objective SCs for bioenergy (Table 23) [257] and has also provided a 10-step GHG inventory framework for biofuels [258]. Challenges lie in agreeing on methods for GHG assessment especially for indirect effects. GBEP is not developing yet another standard or certification scheme. The main soybean producing countries (USA, Brazil, Argentina, China and India) are all GBEP members.

Table 21
Key indicators for biofuels systems.

• GHG emissions (climate change)	• Biodiversity management
• Energy balance	• Land-use change
• Soil health	• Effect on food crops
• Water management	• Air emissions (non-GHG)

After Ref. [250].

Table 22
Ranking of environmental, social and economic criteria for liquid biofuels.[a]

Environmental criteria
- GHG balance
- Energy balance
- Soil protection
- Crop diversity (impact of monocultures)
- Natural resource efficiency
- Water management
- Adaptation capacity to environmental hazards and climate change
- Ecosystems protection (*e.g.* forests)
- Species protection
- Land-use change
- Waste management
- Use of GM organisms (risks)
- Use of chemicals, fertilisers and pest control
- Potentially hazardous atmospheric emissions (non-GHG)
- Exotic species applications
- Ecosystems connectivity (land fragmentation)

Social criteria
- Compliance with laws
- Participation (stakeholders)
- Planning (management plan, objectives)
- Monitoring of criteria performance
- Food security
- Respect for human rights
- Labour conditions of workers
- Property rights and rights of use
- Land availability for other human activities than food production
- Respect of minorities
- Noise impacts
- Cultural acceptability
- Social cohesion
- Standard of living
- Visual impacts

Economic criteria
- Microeconomic sustainability (payback period)
- Economic stability
- Employment generation
- Macroeconomic sustainability (trade balance)

After Ref. [250].
[a] In descending order of importance within each category.

9.2.1. EU-27 biofuel sustainability criteria

It is the policy of the European Union to encourage the production and use of more energy from renewable sources. Therefore, the European Parliament and the Council of the European Union have adopted the Renewable Energy Directive 2009/28/EC (EU-RED) that sets mandatory national targets for the overall share of energy from renewable sources and for that from renewable sources in transport [12]. EU-RED also includes a set of mandatory SCs as part of an EU sustainability scheme [12]. Similar sustainability requirements were set in the Fuel Quality Directive 2009/30/EC (EU-FQD) [259]. Biofuels (domestically produced or imported) are required to fulfil all SCs to count towards EU or national targets and to be eligible for financial support. EU has set the highest sustainability standards in the world. The entire biofuels' production and supply chain has to be sustainable.

Table 23
GBEP sustainability indicators for bioenergy.

Environmental	Social	Economic
• Life-cycle GHG emissions	• Allocation and tenure of land for new bioenergy production	• Productivity
• Soil quality	• Price and supply of a national food basket	• Net energy balance
• Harvest levels of wood resources	• Change in income	• Gross value added
• Emissions of non-GHG air pollutants, including air toxics	• Jobs in the bioenergy sector	• Change in consumption of fossil fuels and traditional use of biomass
• Water use and efficiency	• Change in unpaid time spent by women and children collecting biomass	• Training and re-qualification of the workforce
• Water quality	• Bioenergy used to expand access to modern energy services	• Energy diversity
• Biological diversity in the landscape	• Change in mortality and burden of disease attributable to indoor smoke	• Infrastucture and logistics for distribution of bioenergy
• Land use and land-use change related to bioenergy feedstock production	• Incidence of occupation injury, illness and fatalities	• Capacity and flexibility of use of bioenergy

After Ref. [257].

Verification of compliance with the SCs is left to the Member states. The EU sustainability criteria contained in the EU Energy and Climate Change Package (CCP) go into effect at different times in various Member states (after December 2010), *cf.* Section 9.4. Sustainability rules are expected to favour the use of feedstock that is certified to be sustainable according to a voluntary EU-accredited system, *cf.* Table 25.

EU-RED (Art. 17) excludes several land categories, applies the cross-compliance rules of the Common Agricultural Policy (CAP), requests a minimum for GHG savings relative to fossil fuels, includes a methodology for calculation of GHG emissions, provides guidelines for the calculation of land carbon stocks, and includes monitoring and reporting requirements. Although there are no criteria for social sustainability, biofuels impact and social aspects must be reported. Several aspects not explicitly covered by the SCs in EU-RED, such as environmental and social issues, should be covered by other certification systems and bilateral agreements. The system of proving compliance with SCs complicates biofuels export to the EU.

As to land use, EU-RED excludes land with high biodiversity value or high carbon stock and certain agro-environmental practices for the production of raw materials for biofuels. In practice this means that biofuels made of crops grown on land that used to be rainforest or natural grassland with a unique ecosystem cannot be considered as sustainable. The potential impact of EU-RED on European land use and biodiversity has been assessed [260]. Land-use change is a key driver of change in biodiversity value due to its effects on habitat quality and quantity. However, as the area of semi-natural vegetation, forest and high nature value farmland directly replaced by biofuel crops is relatively small, the direct effects of the directive on European land use and biodiversity are relatively minor. Moreover, cultivation of biofuels is preferred at locations with overall good agricultural quality. These locations are mostly already under agricultural use. Therefore, not much natural vegetation is directly replaced by biofuels. The indirect effects of EU-RED on European land use and biodiversity are much larger than its direct effects. Indirect effects need explicitly to be taken into account in assessing the environmental effects of biofuel crop cultivation and designing sustainable pathways for implementing biofuel policies. Direct and indirect effects of the biofuel directive in countries outside the EU were not considered. The reporting obligation of EU-RED addresses the competition for food and feed, energy supply, bio-materials and green chemistry and other indirect effects. However, reporting alone does not limit such effects.

As shown in Sections 9.2 and 9.4, initiatives regarding SCs for biomass have been taken by various private European organisations. Work is also being undertaken by the European standardisation organisation CEN.

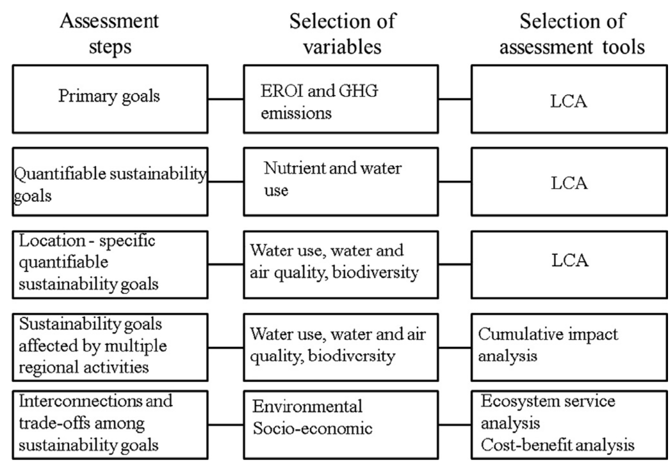


Fig. 8. Stepwise framework for assessment of sustainability of soy biodiesel. After Ref. [263].

9.3. *Assessment of sustainability*

Sustainability assessment is rather new and constitutes an extremely complicated and challenging task in particular due to the lack of a unique, objective, and commonly agreed standardisation methodology [261]. This is reflected in the number and scope of existing initiatives and certification schemes. Apart from climate change and tropospheric ozone formation most of the environmental impacts, as well as social and economic impacts, are more relevant on a local/regional scale.

The entire life cycle of a product must be considered before it can be classified as sustainable. Determining the sustainability of soybean biodiesel production and use requires comparison with other fuels being used today to assess whether substituting soy biodiesel for an existing option (in particular, replacing petroleum-based fuels) improves the sustainability. A stepwise framework for assessment of the sustainability of soy biodiesel (Fig. 8) starts with considering the primary goals for developing alternative liquid fuels, namely improving energy security and reducing GHG emissions. This evaluation (of LCAs) has been carried out for the globally most significant soy biodiesel pathways [262]. It has been suggested by some authors that EROI > 3 is a condition for any fuel to be considered sustainable. Next, variables reflecting commonly agreed-upon sustainability objectives are to be assessed (using LCAs) that can be estimated from mass balance and/or engineering practices, such as nutrient (N, P, K) budgets and water use. Such a commonly agreed-upon objective is for instance avoiding

competition for these resources between food, feed and fuel production. When the industry further develops the effects of potential land-use changes need to be assessed. An overall and comparative assessment of sustainability is complicated by the fact that while some sustainability objectives (*e.g.* resources use or emissions) can be measured or estimated and compared across systems the impact of biological effects (*e.g.* biodiversity) and some environmental effects, for example water use in relation to local availability or hazardous atmospheric emissions (SO_X, CO, NO_X, and particulates) released to the air, soil, or water, causing various impacts, including acidification, eutrophication, ecotoxicity and human toxicity, are mostly mainly site or regional specific. Site-specific factors are suitable topography, microclimate, proximity to sustainable freshwater supplies and to sustainable and economic fertiliser supplies. Also, enough land should *locally* be available for food production, including agricultural set-aside land; marginal sites are to be preferred for energy crops. The environmental effects in one region may not be directly comparable to another (*e.g.* land-use change). The effect of soybean cultivation for biodiesel on biodiversity can only be assessed for specific locations and species (*cfr*. Table 24). Not all of these effects might be easily quantifiable. National or regional initiatives have developed to adapt international standards (*e.g.* ISCC, RTRS, RSPO) to local conditions.

Given the multiple resource requirements and potential environmental effects, specific sustainability concerns cannot be considered in isolation from others. Any one LCA for a single resource use or environmental effect is insufficient to determine the overall sustainability of a soy biodiesel production system. As the soy biodiesel industry develops, the ability of different pathways for soy biodiesel production to balance fuel productivity with other environmental and socio-economic goals has to be assessed in a holistic manner. Challenges arise regarding how to balance the environmental objectives against the economic and social objectives of sustainable development. Trade-offs among sustainability goals should be acceptable to all stakeholders (farmers, soy biodiesel producers, fuel consumers, environmentalists, *etc.*).

Some procedural tools for defining sustainable policies and verifying environmental compatibility are Environmental Impact Assessment (EIA), Environmental Life-Cycle Assessment (E-LCA) and Sustainability Analysis (SA). LCA studies of biodiesel tend to focus on global resources and regional to global environmental impacts. SD assessment tools more easily include local impacts than life-cycle assessment. Operational instruments related towards the evaluation of environmental, economic and social aspects include Material Flow Analysis (MFA), Substance Flow Analysis (SFA), Energy/Exergy Analysis (EA), Risk Assessment (RA), and for cost aspects Life Cycle Costing (LCC), Cost–Benefit Analysis (CBA) and Eco-Efficiency (EE). Social Life-Cycle Assessment (S-LCA) and Socio-economic Life-Cycle Assessment (Social-LCA) are important aspects in sustainability assessment.

Life Cycle Sustainability Assessment (LCSA) consists in the integration of E-LCA, LCC [264] and S-LCA [265]. There is a trade-off between interests. As shown by LCSA of used cooking oil (UCO) waste management, a system with a more positive social behaviour presents a larger environmental and economic cost; on the other hand, a system with lower environmental impact has a lower social component [266]. Environmentally viable and economically efficient alternatives do not always contribute to social deployment. Sustainability assessment helps in sustainable product development.

Table 24
Number of different species in oilcrop cultivation areas in Brazil, Malaysia and Sweden.

Areas	Trees	Other vascular plants	Mammals	Birds	Butterflies
Brazil, Cerrado area	429	4000–10,000	67	400	1000
Malaysia, lowland rainforest	2398	8000–10,000	203	460	1014
Sweden, rural agricultural areas	10–20	1000	35	50	50

After Ref. [160].

9.3.1. Environmental sustainability

Major stages in the biodiesel life cycle are feedstock production (crop cultivation), crushing and vegetable oil extraction, transesterification and use. As to the environmentally prevailing agricultural stage (up to the oil mill), sustainability issues comprise planned land management, agricultural practices, soil conservation, integrated pest management, waste management, effluent treatment and oil mill waste recycling. Environmental degradation through biofuel production may occur through (i) land-use changes; (ii) intensification of agricultural production (*i.e.* increased use of agrochemicals and waste resources); (iii) release of carbon from natural carbon sinks; (iv) displaced food production; and (v) unregulated use of GM feedstocks (outside the EU). Soil erosion is an important driver for land-use change [267]. The environmental impact is reduced by raw materials that are manufactured responsibly from renewable sources, are produced regionally or further improve the energy balance. The environmental impacts of biofuels can very easily exceed those of mineral diesel. The carbon saving potential of biofuel production is low [268].

Protection of the atmosphere, preservation of sensitive ecosystems, conservation of biodiversity and soil fertility, avoidance of soil erosion, conservation of ground and surface water, avoidance of deforestation, desertification and drought, conservation of non-renewable resources and landscape view, are but a selection of ecological sustainability critera. Water demands can easily undermine alternatives to fossil fuels [269], in particular in countries with an already stressed water situation, *cf.* Section 9.1. Tables 20 and 22 list rankings of environmental (and other) sustainability concerns for large-scale production of soy biodiesel and liquid biofuels, respectively. Environmental and ecological sustainability are integrally related to social welfare.

The net benefit of biodiesel production from energetic, environmental and socio-economic perspectives is still widely debated [106,270–275]. Environmental LCA (E-LCA) is about impact on the biophysical environment. E-LCAs ignore social factors and thus do not evaluate complete sustainability. Performance and prospects of soy biodiesel production on a global basis (with emphasis on USA, Brazil, Argentina and PR China) have been assessed on the basis of 30 E-LCAs comparing both agricultural and industrial practices [262]. Soy biodiesel is not a most environmentally sustainable product for all production pathways. Life-cycle energy depends on specific climatic conditions, and on the agro- and processing technologies used. Opportunities have been identified to improve the soy biodiesel life-cycle energy and environmental impact in relevant production areas. Large-scale renewable action plans in the EU and biodiesel mandates elsewhere easily lead to unsustainable consequences. Expanded oilseed production is generally limited by the availability of cropland. While this is a less stringent restraint for some of the major soybean growing countries (Argentina, Brazil), it is more so for USA and in particular for China.

Perceived environmental benefits of soy biodiesel are renewability, biodegradability, non-ecotoxicity and GHG mitigation, but there is little consensus on the degree of sustainability for various agricultural cultivation practices and production methods. Biodiesel production from energy crops could destroy natural habitats

and push up food farming costs in some developing countries. Biodiesel is caught in an environmental dilemma: energy, food or climate. Rapid expansion of agrofuel monocultures is speeding up the destruction of tropical forests and other ecosystems.

Agricultural systems emit carbon through the direct use of fossil fuels for agricultural machinery used in food production, the indirect use of embodied energy in inputs that are energy intensive to manufacture, and the cultivation of soils and/or soil erosion resulting in the loss of soil organic matter. For full sustainability the use of renewable resources is required throughout (thus excluding fossil fuels for transport) [235,236]. Indirect GHG emissions are also on account of fertilisers, pesticides, limestone and electricity. Yet, agriculture is also an accumulator of carbon. Pretty [19] has listed three mechanisms and 21 technical options for increasing carbon sinks and reducing CO_2 and other GHG emissions in agricultural systems. Potential carbon sequestered in soils and above-ground biomass for smallholder farms are 0.35 t C/ha/yr [19]. For large South American farms using zero-tillage and conservation tillage considerable gains in carbon are reported (up to 14.9 t C/ha/yr) [13]. N_2O emissions are produced from nitrogen in the soil through (i) microbial nitrification and denitrification processes and volatilisation of nitrogen from the soil to the air (direct emissions); and (ii) leaching and runoff of nitrate into water streams (indirect emissions) [276]. The uncertainty of N_2O emission calculation is very high [107]. The default methodology proposed by IPCC estimates direct N_2O emissions from soils as a constant fraction (1.25%) of the nitrogen input [277].

Agriculture currently produces 14% of the world's GHG emissions, about the same as the transport or stationary energy sectors. Economic interests are often to be blamed. For instance, large-scale forest clearing in Bolivia in the 1990s for expanding soybean exports was a result of the World Bank's economic development strategy [278,279]. The Global Research Alliance on Agricultural Greenhouse Gases (adhered at by Argentina and USA), launched in 2009, is concerned with developing technologies and practices of producing more food without increasing GHG emissions [280,281]. Organic farming with farm-produced bio-based fuels and without use of industrial fertilisers gives the best overall GHG emissions savings [235,236].

The reduction in GHG emissions on account of biodiesel should not be at the expense of an even larger increase due to deforestation, other land-use changes, NO_X emissions, and potentially the loss of major carbon sinks. Carbon sequestrated by restoring forests might well be greater than the emissions avoided by the use of biofuels [268]. If global warming is to be confined to between 2 °C and 2.4 °C then GHG emissions must be reduced by 50–85% by 2050 [282]. EU-FQD aims at reducing transport fuel emissions by 6% by 2020 [259]. The California Air Resource Board (CARB) adopted a Low Carbon Fuel Standard (LCFS) in 2007 to reduce GHG emissions of transportation fuels. LCFS calls for a reduction of at least 10% of carbon intensity of fuels by 2020. Other US States have committed to developing a regional LCFS program. The carbon intensity, calculated under the LCFS methodology on a full life-cycle basis includes all direct and indirect emissions. The US revised Renewable Fuel Standard (RFS2) programme (2010) requires a 20% reduction of life-cycle GHG emissions (2005 baseline) for renewable first-generation biofuels (soy biodiesel) [283]. GHG emissions include production and transport of the feedstock; land-use change; production; distribution; blending and end use of the renewable fuel. Current farming practices, including land clearing and inefficient use of fertilisers and organic residues make agriculture a significant contributor to GHG emissions [284]. Soy biodiesel shows moderate to good GHG savings without the effects of land-use change [262,285]. EU-RED has set the default GHG emissions saving for soy biodiesel at 31%, *i.e.* below the current minimum requirement of 35% (to increase to a least 50% by 1 January 2018). In practice, these performance levels are difficult to achieve, *cf.* Section 11. Moreover, GHG emissions savings show considerably higher uncertainty than energy savings [286,287], which complicate proof of demonstration of compliance. Large biofuels mandates incur in previously ignored increased GHGs through emissions from land-use change. Changes in soil carbon balances, N_2O emissions and indirect land-use changes are major sources of uncertainty influencing GHG balances of biofuels [270,288].

Although the environmental impacts of the large-scale production of biofuels are mostly focused on the overall carbon footprint, other environmental indicators such as the effects of nitrogen, phosphorus, pesticide and water use are equally important. Fertiliser application rates, which differ greatly for the main soybean producing countries (*cf.* Section 10), are an important determinant of the environmental impact of agriculture. Fertiliser production accounts for a large part of the total energy and exergy use, as shown for CAN N28 and NPK 21-4-7 [289]. Fertiliser rates vary across crop rotations. Both soybean and corn yields are 10–11% higher on average in the non-monoculture rotations across all tillage regimes, though with differences across such regimes [102,290]. Two years of corn between soybean crops increase the soybean crop yield [73].

The rapidly growing biofuel industry adds significant pressure to the environment with damaging consequences for biodiversity. Biodiversity decline should be halted (EU-RED target). EU-RED and various certification schemes (UK-RTFO, US-RFS, ISCC, NTA 8080) require that high biodiversity value land and high carbon stock land (*e.g.* forested areas) should not be used for biofuels production. US-RFS prohibits any new conversion of natural areas for biofuel production by limiting feedstock production on existing actively managed or fallow agricultural lands. It also prohibits conversion of natural grasslands.

Research within the European project ALARM (**A**ssessing **LA**rge-scale environmental **R**isks for biodiversity with tested **M**ethods; GOCE-CT-2003-506675; 2003–2005) has focused on assessment and changes in terrestrial and freshwater biodiversity and ecosystem functioning. In particular, risks arising from climate change, environmental chemicals, biological invasions and pollinator loss in the context of European land-use patterns have been investigated and policy options to mitigate such risks have been indicated [291,292]. The Joint Nature Conservation Committee (JNCC), the statutory advisor to the UK government on nature conservation, has issued a position statement on transport biofuels and biodiversity [293]. JNCC supports the UK efforts to develop international sustainability criteria through the Global Bioenergy Partnership (GBEP), *cf.* Section 9.2.

Land use and biodiversity are intimately connected. Biodiversity is violated by eradicating diversified vegetation and replacing it with monocultural crops. Although the Brazilian Cerrado area – a global biodiversity hotspot [294] – used to be very rich in biodiversity (Table 24), only 1.5% of this land is protected today. Loss of habitat as a result of soybean expansion is the most serious threat to biodiversity in the Cerrado area. If we consider that people prefer a diverse landscape then large cultivation units of soybean and oil palm are less pleasing than crops grown in small fields. Finally, also (continuous or temporary) land transformation needs to be considered [295]. It is reasonable to allocate the resulting environmental impacts, such as loss of biodiversity, to the crop harvested. Soybean cultivation requires approximately 30% more land than rapeseed cultivation and for many of the land-use indicators, *e.g.* soil erosion and biodiversity, it is clear that soybean cultivation carries regionally serious environmental problems. The overarching goal of the Biodiversity and Agricultural Commodities Program (BACP, 2008–2018) of the International Finance Corporation (IFC) is to reduce threats posed by commodity

agriculture to biodiversity of global importance by increasing the volume of sustainably produced and verified commodities by adoption of biodiversity-friendly practice. BACP addresses four commodities (soy, dendê, cocoa and sugarcane) and nine countries, including Brazil [296].

Compared with the existing certification schemes for sustainable agriculture and forestry, which mainly concentrate on air, water and soil impacts (conservation), biofuels certification requires additional SCs to be included, such as carbon stock, GHG emissions, land-use changes, socio-economic demands, *etc*. Moreover, air, water and soil impacts as well as conservation of biodiversity are included to a different extent in agricultural and forest certification. Several environmental criteria are formulated in a rather different way in the various approaches. Some schemes require an environmental impact assessment, others require good farming practice. RSB provides guidance for conducting an Environmental and Social Impact Assessment (ESIA). RTRS includes Integrated Crop Management (ICM) practices. Different requirements also regard biodiversity in the various certification schemes.

9.3.2. Social impact assessment

Biodiesel sustainability requirements comprise social criteria. Social assessment tools are Social Life-Cycle Assessment (S-LCA) and Social Impact Assessment (SIA). S-LCA methodology is in an early stage of development [265,297,298]. There is rising interest in social and socio-economic LCA methodology as a complement to Environmental LCA (E-LCA) [299,300]. S-LCA is about social impacts on people along product life cycles, with focus on human well-being, dignity and health [297,301]. Most social impacts bear little relation to the process themselves but rather reflect the conduct of operators performing the processes. Social LCA aims at facilitating conduction of business in a socially responsible manner and at indicating trade-offs. Impact categories are related to social themes of interest to stakeholders (workers, local communities, society, consumers, traders, *etc*.) and decisionmakers, including human rights, labour practices and work conditions, protection of human safety and health, quality of life, security of food and energy supply, land ownership, fair trade conditions, product responsibility, cultural heritage, poverty, disease, political conflict, indigenous rights, *etc*. The main goal is to detect social hotspots and identify feasible alternatives to potential negative social impacts. S-LCA permits *relative* product comparisons rather than absolute analysis.

Health hazards to man may arise directly or indirectly (through the environment) [302]. For instance, the extensive use of broad-spectrum herbicides with glyphosate, fungicides and insecticides in the non-tillage RR soybean system may impact the health of farm workers and communities (by spill-over) and can have severe effects on biodiversity and aquatic environments, such as rivers and lakes, in the large areas where soybeans are the only crop [92,93].

The perception of social impacts is highly variable and their measurement is complex. The assessment of societal (microeconomic) and social (macroeconomic) impacts involves several hundred specific indicators, including health care, housing, education, human well-being indexes, equal opportunities, contribution to economic development, local employment, working hours, employees with higher education, occupational accidents, freedom of association, corruption, *etc*. [303]. The impact of a societal action is highly local. Social LCA holds the potential of promoting economic and social welfare and improving working conditions. In contrast to E-LCA, S-LCA methodology is more qualitative, highly geographical site-specific in its data requirements, and creates subjective data [297,300]. System boundaries are difficult to define through the entire product life cycle. There is no difference between E-LCA and S-LCA with regard to the functional unit. There is a need for creating databases of social and socio-economic information. There are generally no S-LCA databases on biodiesel production.

Socio-economic aspects are key factors for sustainability certification. Although no specific criteria for social sustainability are included in EU-RED the European Commission is to report on the biofuels impact on social issues and on the availability of food at affordable prices. Global-Bio-Pack (EU FP7-245085, 2010–2013) develops a set of socio-economic sustainability criteria and indicators for biomass production, conversion and trade for inclusion in a future effective certification scheme [304].

Various certification schemes, such as RSB and RSPO, require a Social Impact Assessment to assess the impacts on various social aspects due to biofuels production, on the basis of social guidelines. The social and economic performance indicators of the Global Reporting Initiative are used in NTA 8080 to monitor the social well-being of local communities. While meeting the socio-economic principles of UK-RTFO are not obligatory in implementation, they are a must in NTA 8080. Development of a common approach to socio-economic impacts is highly needed. Ratification of ILO conventions is seen as a minimum requirement (ISCC, RSPO, UK-RTFO, RTRS). Monitoring and enforcement of social criteria depends on the law enforcement in each country. Mbohwa et al. [27] have applied S-LCA and Social-LCA to biodiesel in South Africa using methods developed by UNEP [300].

9.4. Biofuels certification

Certification is the process whereby an independent party (the certification body) assesses the quality of management in relation to a set of predetermined requirements (the standard). Certification is based on the justified confidence that a product, service, process or system complies with (internationally) agreed standards. Certification addresses governmental guidelines for biomass minimum standards, usually in combination with a set of private standards higher than those mandated by law. Certification schemes ease (inter)national trade. Biomass certification schemes have to comply with international trade regulations (WTO).

For the agricultural sector several (private sector) voluntary certification systems exist (*e.g*. Global G.A.P. [21], IFOAM [305], SAN [306], *etc*.), which reflect different forms of farming, *i.e*. organic, integrated or GAP. These systems were primarily designed to ensure health and safety of given products and their environmentally friendly or sustainable agricultural production. An environmental label for organic farming, where nutrient management is of high importance, was introduced in Europe in 1991 [307]. Agricultural certification schemes verify the sustainability of farming practices (mainly environmental aspects), agrochemical handling and use, safety and health, and food traceability. Land-use change aspects and energy balance are not considered important in agricultural certification. Various initiatives focus specifically on the sustainability of soybean production. The development of certification schemes for crops used as feedstocks for biofuels from tropical countries, such as Round Table on Responsible Soy (RTRS), Roundtable on Sustainable Palm Oil (RSPO), and the Better Sugarcane Initiative (BSI), is essential for securing various sustainability concerns. In the forestry sector certification was introduced in 1993.

The more recently developed certification initiatives concern crops used as feedstock for biofuel (*cf*. Table 25). Biofuels certification is a response to the concerns related to their sustainability. Initiatives taken vary from each other, *e.g*. depending on the scope of the application, the validity, the extent, issues considered for environmental, social, and economic aspects, and on conditions set for fulfilling the sustainability criteria.

Table 25
Voluntary biofuels sustainability schemes recognised by the European Commission.[a]

Sustainability scheme	Coverage
• International Sustainability and Carbon Certification (ISCC)	All kinds of feedstock in all regions
• Bonsucro EU Mass Balance Chain of Custody Standard	Sugarcane in all regions
• Round Table on Responsible Soy (RTRS EU-RED)	Soybeans outside the EU
• Roundtable on Sustainable Biofuels (RSB EU-RED)	All kinds of feedstock in all regions
• Biomass Biofuels Sustainability voluntary scheme (2BSvs)	All kinds of feedstock in all regions
• NTA 8080	All kinds of feedstock in The Netherlands
• Abengoa RED Bioenergy Sustainability Assurance (RBSA)	All kinds of feedstock in all regions
• Greenenergy Bioethanol verification scheme (Greenenergy)	Sugarcane in Brazil
• Ensus voluntary scheme	Ensus bioethanol
• Roundtable on Sustainable Palm Oil (RSPO RED)	Palm oil in all regions
• Red Tractor (Red Tractor Farm Assurance Combinable Crops & Sugar Beet Scheme)[b]	Food crops and sugar beet in Britain
• SQC (Scottish Quality Farm Assured Combinable Crops Scheme)	Food crops and rapeseed in Scotland
• REDcert	All kinds of feedstock in Europe

[a] Approved since 24 July 2012.
[b] Formerly ACCS.

Depending on their main goal, the various certification schemes developed for biofuels sustainability include a selection of environmental, economic and social aspects. However, certain specific issues are often underdeveloped, such as indirect effects, food availability and security. Certification has the potential to secure certain sustainability goals through proper enforcement and verification mechanisms and to positively influence direct environmental and social impacts of bioenergy production [308]. It has been argued that only a certification scheme addressing biomass feedstock production (cultivation) – regardless of the final use (food, feed, fuel, materials) – might be able to avoid different impacts, either direct or indirect [309]. To ensure credibility a certification system should include a wide variety of stakeholders. Different stakeholder groups ((supra)national governments, intergovernmental organisations, NGOs, international or regional bodies, industrial operators), which have recognised the need for biomass sustainability criteria, all have different interests in biomass certification [254].

A large number of (inter)national and supranational initiatives have been developed in view of the biofuels and bioenergy targets announced worldwide. EU governments no longer view the rapid increase in biofuel consumption as a priority, and this has contributed to a decline in growth of biofuel consumption in transport from 41.7% in 2007/2008 to 3.0% in 2010/2011. On a European level, the EC has established the RED sustainability criteria (*cf*. Section 9.2.1) and actively verifies compliance of biofuel used in the Member States. Several national governments have taken initiatives to develop biomass certification systems (*e.g.* Germany, The Netherlands, UK, Brazil, Argentina and USA) [255]. European initiatives for biofuel certification include the International Sustainability and Carbon Certification (ISCC, Germany), Renewable Transport Fuel Obligation (RTFO, UK), Netherlands Technical Agreement (NTA), and others. The German ISCC initiative – with 250 stakeholders – has finalised an international certification scheme for all kinds of biomass and bioenergy, and is oriented towards reduction of GHG emissions, sustainable use of land and protection of natural biospheres [310]. ISCC is supported by the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) via the Agency for Renewable Resources (FNR). The ISCC standard comprises six principles and corresponding criteria (ISCC 202) [310]. ISCC requires a GHG emission reduction of 35%. The GHG emission calculation methodology (ISCC 205) considers all emissions in the life cycle of the production chain, including transport and by-products (with energetic allocation). It also considers emissions from land-use change. After pilot testing in EU, Argentina, Brazil and Malaysia the ISCC system has been recognised by the German Federal Agency for Agriculture and Food (BLE) and the EC. Approximately 95% of the 2010 German rapeseed harvest has been certified on sustainability [26]. On 1 January 2011 the German biofuel sustainability law (Biokraft-NachV) came into force, making Germany the first country to comply with the sustainability prescriptions of EU-RED. Another German certification system, REDcert, fulfils the requirements of the German Biomass Sustainability Ordinances (BioSt-NachV and Biokraft-NachV).

The Renewable Transport Fuel Obligation (RTFO) requires that a certain amount of road transportation fuels in the UK come from sustainable renewable sources [311]. RTFO has established the Sustainability Reporting and Carbon Certification, including a methodology for GHG savings [312]. RTFO sustainability reporting covers seven environmental and social principles and criteria: carbon conservation, biodiversity conservation, soil conservation, sustainable water use, air quality, workers rights and land rights. E4Tech has carried out a feasibility study on GHG certification in relation to effective operation of RTFO [313]. RTFO certificates are issued based on GHG savings (set at 50% for 2010/2011) determined through a standardised GHG certification system. As part of the GHG certification a criterion on avoiding deforestation has been included. Other environmental and social criteria are covered by a separate voluntary scheme (not directly linked to RTFO). Since 15 December 2011 UK's RTFO has been amended to implement RED's sustainability criteria. Eligibility for sustainable fuel certificates – Renewable Transport Fuel Certificates (RTFCs) – depends on meeting these criteria. The UK has increased its sustainable biofuel incorporation volume from 3.5% in April 2011 to 5% in April 2013. The actual incorporation values of 2.4% and 3.1% in 2009 and 2010/2011, respectively, fall short of the intended obligation.

A working group of the Dutch Standards Organisation (NEN) has developed the Netherlands Technical Agreement (NTA) with sustainability criteria for biomass. NTA 8080:2009 ‘Sustainability criteria for biomass for energy purposes’ includes the minimum requirements to be used for the certification of sustainably produced biomass for energy production. The Dutch criteria for sustainable biomass production focus on GHG balance, competition with food and other applications, biodiversity, environment, prosperity, and social well-being [239]. NTA 8081 is the corresponding voluntary certification scheme, which is recognised by the Dutch Council for Accreditation (Nederlandse Raad van Accreditatie) [314]. The system requires segregation on mass balance as the traceability system. The Netherlands is number 2 soy importer in the world (after China) and number 1 importer in Europe. 100% of Dutch processing and consumption is certified soy. In 2007 palm oil has been excluded from the Dutch Renewable Energy Incentive (SDE) subsidy scheme because of unsustainable production.

2BSvs is a French industry scheme covering all types of biomass and biofuels [315]. The 2BS Consortium is an association of professional syndicates representing the biofuels industry in France. RBSA (RED Bioenergy Sustainability Assurance) is an industry scheme developed by the Spanish Abengoa covering their supply chain. The method for compliance certification with the SCs used in the RBSA method is the mass balance system, as stipulated in EU-RED [188]. In 2008 the European Committee for Standardisation (CEN) established the CEN 383 Committee for ‘Sustainably produced biomass for energy applications’ to elaborate a European standard for sustainable biomass for energy applications.

In the US, reference is made to the United States Renewable Fuel Standards (RFS, RFS2) and the California Low Carbon Fuel Standard (LCFS). In South America, the CARBIO (Cámara Argentina de Biocombustibles) Sustainability Certification Scheme (CSCS) has been developed to demonstrate the sustainability of Argentine soy biodiesel and its inputs (biomass, intermediate products), in conformity with EU-RED [316]. However, CSCS is not yet EU compliant (*cf.* Table 25). In Brazil (2008) certification systems for biomass and biodiesel are emerging such as the Social Fuel Stamp (SFS), *cf.* Section 5.1.

On an international level, activities to develop a biomass certification system are initiated by international organisations, networks and roundtables in which various stakeholders participate. Such initiatives comprise the Roundtable on Sustainable Biofuels (RSB), Round Table on Responsible Soy (RTRS), Council on Sustainable Biomass Production (CSBP) and ISO/PC 248 [245]. Roundtable on Sustainable Biofuels (RSB), established in 2006 and joined by UNEP, aims to achieve global, multi-stakeholder consensus around the principles and criteria of sustainable biofuels production and builds on existing national and community-based initiatives [317,318]. The RSB standard includes 12 principles (legality; planning, monitoring and continuous improvement; GHG emissions; human and labour rights; rural and social development; local food security; conservation; soil; water; air; use of technology, inputs, and management of waste; and land rights), and criteria and requirements differentiated in minimum and progress requirements for four categories of operators (feedstock producers, feedstock processors, biofuel producers and biofuel blenders) [318]. The RSB criteria aim to address only the direct activities that farmers and producers can undertake to prevent unintended consequences from biofuel production. Many large-scale impacts are less easy to address at an individual operator level. All RSB criteria are in agreement with the sustainability requirements laid down in EU-RED. The first compliance certificates were issued in 2011. RSB does not attempt to quantify the amount of biofuels which could be sustainably produced, or whether, as a whole, biofuels are sustainable.

The different schemes are highly inconsistent on the issue of GHG emissions with different calculation methodologies, minimum targets, boundary conditions, reference years, *etc*. The required GHG reduction levels vary from 20% (US-RFS) to 50% (RSB). GBEP strives towards harmonisation of methodologies to calculate GHG emission reductions [258]. No specific GHG reduction requirement is included in the RTRS standard (*cf.* Section 10.1.2). RTRS criterion 4.3 calls for efforts to reduce emissions and increase sequestration of GHG on the farm. RTRS developed an EU-RED add-on to get recognition as a voluntary scheme, including GHG calculation. RSB has developed its own GHG accounting methodology (not dissimilar from EU-RED calculation procedures), based on economic allocation, without (as yet) taking ILUC into account [319]. Use of allocation trades environmental relevance for expediency. Operators in areas where EU-RED is applicable must also comply with this scheme. RSB biofuel blends shall have on average 50% lower life-cycle GHG emissions relative to the fossil fuel baseline, which increases over time. It is beyond the scope of this paper to describe all certification schemes in detail.

Out of the 19 certification schemes proposed to the EU Commission on the Sustainability of Biofuels and Bioliquids 13 voluntary schemes have been recognised since 24 July 2012. EU recognition is for five years [320]. Economic operators have three possibilities of demonstrating that the EU-RED sustainability criteria for biofuels, including imports, are upheld: (i) voluntary EU recognised certification (*cf.* Table 25); (ii) agreement with a specific Member State; and (iii) bi- or multilateral agreements between the EU and third-party countries (not currently in existence). Certificates from a voluntary but not approved sustainability scheme, for instance CSCS, are not accepted. It is possible to use the option of ‘default values’ laid down in the EU-RED Directive to show compliance with the sustainability criterion on GHG emissions savings.

The sustainability of biofuels needs to be checked by the EU Member States. According to EU regulation 1221/2009 as from 1 July 2010 biofuels in the EU will need a ‘proof of sustainability’ (POS) certificate from an approved sustainability system in order to be eligible for tax incentives or mandates. Soybeans and soybean oil can be exported without a POS certificate if the soybean oil is used for food production or if the final biofuel neither receives any tax incentive nor is used to comply with a mandate. Compliance verification of the RED SCs has started in Germany (as from 1 January 2011) [321]. The French national sustainable biofuel and bioliquid system came into force on 10 November 2011 and will be implemented before 30 April 2012. Spain's national biofuel SC certification system dates from 4 November 2011 (Royal Decree 1597/2011) and will enter in force by 1 January 2013. In Italy, the national biofuel certification system came into force on 8 February 2012. Other EU Member States are following quickly.

Certification also implies traceability. A chain-of-custody creates a direct link between the production site and final product. In the case of biofuels, actual GHG emissions data must be provided on the feedstock cultivation stage, as well as additional data on each of the subsequent steps in the supply chain, including transport and conversion. The US Energy Independence and Security Act (EISA 2007) requires full feedstock certification back to the origin (land, slaughterhouse or restaurant). The entire biofuels’ production and supply chain has to be sustainable. Mixing of certified and uncertified biomass *cq*. biofuels should be prevented. Archer Daniels Midland Co. (ADM) has shown the EU Commission that certain South American farms meet the EU's environmental criteria according to EU-RED and that their soybean will not be contaminated with those from non-audited farms [322]. EU-27 and Japan largely depend on Brazil for imports of conventional (non-GM) food-grade soybeans. Traceability of non-GM *vs*. GM soybeans is difficult and expensive. The trade implications of the certification policy favour Brazil and Bolivia in the EU-27 GMO-free soy export market.

Many criteria (such as land-use change) are not covered within most certification systems [255]. While DLUCs are included, ILUCs are not in most systems, despite the fact that these are acknowledged being even more important. RSB, NTA 8080 and LCFS consider ILUC. There are different views on how to best define and quantify criteria for indirect land-use change. Some hold the view that due to their global complexity, ILUC effects should not be included in certification schemes [309]. Various options for dealing with ILUC have been considered: (i) the use of an ILUC factor; and (ii) promoting practices and feedstocks that lower the risk for negative indirect impacts [323]. EPA is currently developing ILUC-values for several feedstocks in the US-RFS. Similar efforts are made in the EU to include ILUC in the GHG emissions calculation for EU-RED requirements. It is noticed that the US-RFS and the

Californian LCFS address ILUC impacts by using a consequential LCA rather than calculating ILUCs. However, ILUC may be minimised by the use of more efficient feedstocks, waste and residues, increasing crop yields, cultivation on fallow or degraded land. Soybean is not to be ranked among the more efficient feedstocks. The EU has not yet made a decision on how to address indirect impacts in EU-RED but provides incentives for promoting biofuels made from waste residues, non-food cellulosic and lignocellulosic material and the use of degraded and contaminated land [12]. Similarly, RFS (USA) and LCFS (California) contain incentives for promoting advanced biofuels with little ILUC impact. While RSB recognises the importance of the issues of indirect impacts (in particular ILUC) (Criterion 3b) a mechanism to promote biofuels at lower risk of causing negative indirect impacts needs further development [324].

Some certification schemes require process improvements over time (RTRS, RSPO), others require achievement of specific targets (EU-RED, RSB, RTFO). Several certification schemes have been benchmarked against the UK-RTFO standard. The RSB standard covers only partially the environmental and social criteria from the RTFO. This has implications for export of such certified products to the UK. Some standards meet the Qualifying Environmental Standard level, or the Qualifying Social Standard level (*e.g.* RTRS, RSPO). Various schemes specify the chain of custody, accreditation and verification requirements (RSB, ISCC, NTA 8080, RTRS).

The various certification schemes, as well as EU-RED, differ also in monitoring and reporting requirements. For instance, UK's RFA monitors and reports on environmental and social issues and the indirect impacts (*e.g.* ILUC) of biofuel production. In the United States, EPA is in charge of reporting on a wide range of impacts of biofuels, such as GHG and non-GHG (pollutant) emissions, impacts on water, economic impacts, *etc*.

Biofuels certification has its limitations. As shown in Section 9.2, biofuels certification faces considerable difficulties in formulating sustainability criteria. As certification systems for sustainable bioenergy production cannot cope with macro-level impacts such as food prices and displacement, they need to be complemented by other tools, including instruments aiming at more sustainable agriculture and forestry, policies emphasising energy efficiency and an effective land-use policy in order to address macro-level impacts [244]. Poor law enforcement may lead to reduced effectiveness for certification. Preventing negative land-use changes requires a verifiable land use and sustainable land management policy and adequate tools to identify and prevent them. Land use can be monitored using high-resolution satellite imaging, *e.g.* Brazil's control on deforestation [115,116,191] and EU's verification of the implementation of its CAP [325]. Moreover, certification schemes established on the basis of the final use of a crop might be highly ineffective in securing sustainability. In order to avoid indirect displacement effects a common-standard policy is required for food/feed/fibre and biofuel production [309].

There is an open market for certification systems. Recent years have witnessed the development of a bewildering number of (inter) national approaches for the sustainability certification of biofuels and of crops used as feedstocks for biofuels. The present proliferation of competing standards and certification schemes, all with significantly different parameters, GHG calculation methodologies, monitoring and reporting requirements, lacks uniformity and transparency, causes confusion and loss of credibility, and may even obstruct the development of a sustainable fuels market. Existing sustainable biomass certification systems lack coherence. Sustainability criteria are internationally not interpreted in an equivalent way. There is the risk that the quality of certificates is variable. A global, generic and comprehensive sustainability framework for bioenergy is auspicable. A standardised international system for biofuels would eliminate the need for multiple systems and provide uniform requirements. CEN works to elaborate a European standard for sustainable biomass. The main aim of the EU Global-Bio-Pact project (FP7-245085; 2010–2013) is the development and harmonisation of global sustainability certification systems for biomass production, conversion systems and trade in order to prevent negative socio-economic impacts [304]. Emphasis is placed on a detailed assessment of the socio-economic impacts of raw material production. Next to certification, policy tools are needed to ensure sustainable biomass production (monitoring of land use). For overviews of recent developments in sustainable biomass/biofuels/bioenergy certification, *cfr*. refs. [255,309].

10. Agricultural management practices in soybean producing countries

Table 26 lists the drivers for biodiesel production within the national energy policy for the main soybean producing countries in comparison to the European Union. Energy security is the main driving force for most countries while EU strongly emphasises sustainability, Brazil social aspects and biodiversity and Argentina trade balance. The recently adopted Low Carbon Agricultural program (ABC) is a turning point in Brazil's attention for mitigating climate change. Despite important differences in focus, there is a common motivation for biodiesel development in South American countries (Table 27).

There are considerable differences in land-use history and agricultural practices between North and South America [327]. The tropical zones of South America have recently experienced slash-and-burn and conversion of forest ecosystems to transient agriculture and low-input agriculture. Oilcrop production in Argentina differs from Northern production modes essentially in the following characteristics:

- larger production scales (planting consortia of 10 kha are not uncommon),
- greater use of no-tillage practices (100% in Argentina *vs*. 50% in USA [125]),
- higher soybean yields,
- higher rates of modern technology: new machinery, precision agriculture, extensive use of GMOs (100% in Argentina *vs*. 93% in USA, 2011),
- development of efficient planting, spraying and harvesting services: high use of farm machinery,
- low fertiliser input agriculture (*cf*. Fig. 9),

Table 26
Bioenergy policy of soybean producing countries *vs*. EU.

Country	Driver
USA	Energy security, low-carbon transport
Brazil	Fuel supply diversification, social inclusion and regional development, biodiversity, low-carbon agriculture
Argentina	Diversification of energy supply, reduction of diesel import deficit, export commodity, economic development
PR China	Diversification of energy sources, environmental policy, rural development
India	Diversification of energy sources
EU	Sustainability, competitiveness, security of energy supply

Table 27
Motivation for biodiesel development in South America.

- Availability of a large variety of renewable lipid sources
- Large availability of farming land
- Economy largely dependent on diesel
- Diesel partially imported
- Oil refining facilities near limit
- High energy demand (electricity) in remote areas
- Decreasing air quality in highly populated urban areas
- Need for increasing job availability in the countryside
- Well-established agro-industrial activities
- Export markets

After Ref. [326].

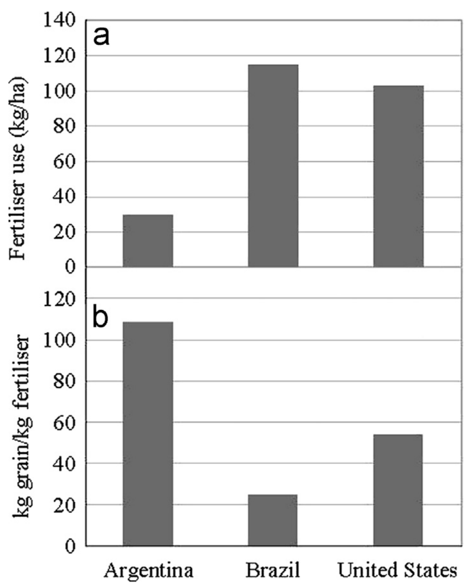


Fig. 9. Fertiliser use and fertiliser use efficiency in Argentina, Brazil and USA. (a) Total fertiliser use per hectare of arable land, and (b) grain produced per kg of fertiliser applied.
Source: FAO (2002).

- energy conservation,
- higher use of agrochemicals.

Argentina and Brazil have favourable climatic and environmental conditions for plant growth, low labour costs, relatively low energy input in agricultural production and hence low production costs for energy crops. Soybean is a dominant crop in these countries, in continuous and rapid expansion with adverse effects upon critical habitats. On the contrary, no such adverse impacts are expected for USA and India.

Inputs used in soybean cultivation and losses to the environment vary strongly depending on cropping system, location and environmental conditions. Optimal agricultural management practice depends on the objective for which crops are cultivated. To obtain an optimal GHG balance, lower fertiliser rates may need to be applied than to attain highest yield levels. Most of the large soybean growers (USA, Brazil, Argentina) have already optimised their production in terms of yield. The quality of the land has a large impact on the attainable yield levels. Clearing of natural lands for cultivation should be carefully selected. Certain soils are sensitive to erosion (*e.g.* Cerrado soils). There is a direct relation between management practices and sustainability aspects such as losses of nutrients and pesticides to the groundwater, emissions of gases to the air, and the fertility of the soil [328].

Savings in GHG emissions are feasible under optimal management practices and proper land use planning. For soybean this implies cultivation in rotation with crops that need to be fertilised with nitrogen. Proper planning of land use involving multi-stakeholder platforms is the most effective way to find on optimal balance between the social, economic and environmental objectives that should be realised in various Latin American regions (Cerrado, Amazonia, Chaco, *etc.*). In general, land use planning in Brazil only takes places on a local scale. The method of cultivating soy in large-scale GM monoculture brings other monocultures (destruction of local culture and traditions) and increases the need to use agrochemicals (pesticides in particular) across the soy chain. It is difficult to see how either voluntary or mandatory sustainability standards can achieve pesticide reduction as long as increased yields are the declared priority of the agro-business [329].

Agricultural expansion has been the primary drive of land-use change in Latin America. Soybean expansion has taken advantage of a suitable climate allowing two harvests per year, relatively easy cultivation of RR soy, low herbicide prices, the introduction of NT farming, modern and efficient production facilities, and the presence of a big export market (demand from EU biofuels obligations). European legislation, intended for environmental protection, has become directly implicated in adverse social and ecological changes elsewhere [329].

(Sub)tropical agriculture requires extensive use of agrochemicals. GM herbicide-resistant crops (HRCs) have been developed for an industrial farming model that involves large-scale monocultures that depend on costly, polluting inputs such as herbicides, synthetic fertilisers and fossil fuels, which are not part of sustainable agricultural practices. Pesticides in soybean cultivation are used in every production stage from pre-seed germination to post-harvest. The use of glyphosate (Monsanto) has allowed the use of NT practices, in which the crop is sown over the stubble of the former crop, facilitating erosion reduction and higher production under intensive agriculture [330]. By adoption of GM glyphosate-resistant (GR) cultivars biotechnology has provided a tool for dealing with weed management in large-scale capital-intensive monoculture [331]. This has initially determined a decrease in consumption of other herbicides (*e.g.* atrazine or 2,4-dichlorophenoxyacetic acid) but recently the consumption of such highly hazardous herbicides is rising again in Argentina [332].

The average glyphosate application rate for soya in the US has doubled in the 1996–2006 period [333]; similar trends were observed for Brazil [334] and Argentina [332]. In Brazil, from 2000 to 2004 the domestic consumption of glyphosate has risen by 95%, outpacing the 71% rise in soybean planted area. The State of Rio Grande do Sul – a main producer of Brazil's transgenic soybeans – has shown an increase of 162% of glyphosate consumption and 38% in the soybean planted area. In Argentina, only herbicide-resistant GM soybean varieties are used that are tolerant to Monsanto's Roundup. Its use has increased from 1 kt in the mid 90s to 20 kt (2000) and 45 kt (2004) [199]. The initial average of 2.1 L of glyphosate per hectare of RR soybeans in 1996–1997 has increased to 10.9 L/ha in 2009/2010. If we consider typical recent application rates of 4–7 L glyphosate/ha for first-class soy and 2.5 L/ha for second-class soy [335] then a conservative estimate of annual Argentine glyphosate consumption amounts to about 80 ML (2008), but much higher values have also been quoted (180 ML for 2007 [329] and 200 ML for the 2009/2010 season [96]). The 6.2–15.4 fold increase in glyphosate use over the 1996–2010 period largely outpaces the 3.0 fold increase in soy-cultivated area or the 4.5 fold increase in soybean productivity.

One of the central arguments for the use of GM crops has been the reduction of pesticides. However, the aforementioned figures for soy-growing countries are proof that this argument is

untenable. Monsanto's promise of reduced herbicide use and easier weed control have not been delivered. Both Argentina and Brazil still make use of toxic herbicides, no longer used on the European market, such as the presumed human carcinogen acetochlor. The South American agrochemicals practices should be compared to the restrained herbicide use of 0.73 kg/ha (2000) to 1.34 kg/ha (2005) in USA [126,336].

Weed control by glyphosate is accompanied by increasing health, biodiversity and environmental concerns and the development of weed resistance. Glyphosate-based products can have adverse impacts on human and animal health [92,93,329,330], as everything used in overdose. Leaching of glyphosate has serious implications for aquatic life and biodiversity. For a discussion on human health impacts derived from glyphosate utilisation in Argentina, *cfr*. Ref. [302]. The European Food Safety Authority (EFSA) is in the process of assessing glyphosate.

Increased reliance on a single herbicide is a disadvantage of no-till systems and accelerates the emergence of genetically resistant weed phenotypes [332,337], *cf*. Section 3.1.1. After 15 years of massive glyphosate use, weed resistance to glyphosate has been built up in numerous species. The first GR weed – horseweed (*Conyza canadensis*) – was recorded in soybean cultivation areas already in 2000 [338]. Johnsongrass (*Sorghum halepense*) was the first GR weed observed in Argentina in 2002 and is spreading rapidly [332]. In 2010 some 115 resistant strains were on record with a total infested area of 5.96 Mha [330]. In rotation of soybean with other crops the diversity of herbicides used increases, which decreases the risk for weed resistance.

Biotech companies have launched novel GM crops with new herbicide-resistance as a response to the appearance of GR weeds [98], *cf*. Tables 10 and 15. STS® (Pioneer Hi-Bred Intl.) is a glyphosate and sulfonylurea-resistant soy variety. DuPont has also developed the multiple herbicide-resistance GAT/HRA technology for soybean, corn and other crops [339]. GAT/HRA combines metabolic glyphosate inactivation with an acetolactate synthase (ALS) enzyme that is insensitive to ALS-inhibiting herbicides.

Insect pest pressure is increasing in Argentina, where insecticide seed treatments are common and needed as a consequence of repeated use of NT practices. The pyrethroid cypermethrin, a possible human carcinogen and highly toxic to aquatic environments, is widely used, as well as Lorsban 48E (Dow AgroSciences) and the off-patent Endosulfan [335]. The latter insecticide, already banned in USA and Brazil and under the Stockholm Convention as from mid 2012, will be phased out in Argentina as from 1 July 2013. Also soy plant diseases and fungal infections constitute a problem. The fungicide Opera® (BASF) is widely used [335].

Overviews of the use of seeds, fertilisers and agrochemicals in South American soybean cultivation practices generally indicate considerably higher fertiliser use in Brazil than in Argentina [107,335], as also confirmed in Fig. 9. This is despite the fact that genotypes selected for maximum BNF do not need any fertiliser N in soybean production on low fertility Brazilian soils [132]. In Argentina, soybean has long been cropped without fertilisation, although soil phosphorus contents have decreased (especially in the Pampas). Despite the low N fertiliser application, Argentina boasts top fertiliser efficiency (kg grain/kg fertiliser applied) – four times higher than in Brazil – because of the highly fertile Pampa soils (Fig. 9b). The average N application (fertiliser) to soybean fields in the Pampas was only 2 kg N/ha in 2002 [340], *cf*. about 3.7 kg in USA [33]. The intensification of the Argentine production system was followed by a decline in soil fertility and increase of soil erosion. Fertiliser consumption stepped up from 0.3 Mt in 1990 to 3.37 Mt in 2010. The increase in total fertiliser use far exceeds the increase in total production in the same period. Argentinean fertiliser consumption is far below South American average [135]. Consequently, nutrient depletion and soil erosion in the Pampean region come to no surprise (Table 28). The relatively low-input agriculture in combination with the high fertility of the soils in the Pampa region has resulted in a net negative balance for nitrogen and other elements [327]. With current agricultural practices, the amount of nitrogen applied as fertiliser or gained through crop BNF is not sufficient to compensate for losses due to seed export. These practices essentially determine 'mining' of the nutrient capital of the region. Argentina is facing an important degradation of soil and biodiversity.

Table 28
Nutrient depletion in the pampean region.[a]

Soil characteristic	Original[b]	Cropped[c]
Organic matter (%)	5.3	3.5
pH	6.2	6.0
Total N (g/kg)	2.8	1.9
Bray P (mg/kg)	123.5	14.9
Exch. K (cmol/kg)	2.3	1.3
Exch. Ca (cmol/kg)	10.1	10.0
Exch. Mg (cmol/kg)	2.4	1.9
Zn (mg/kg)	3.9	1.9
Cu (mg/kg)	3.5	2.4
B (mg/kg)	0.77	0.28

After Ref. [135].

[a] Typic Argiudoll – Arroyo Dulce Series.
[b] Undisturbed for at least 18 years.
[c] Annual cropping for 30 years (20 yr soybean).

In North Italian soybean cultivation fertiliser consumption is considerable, namely 80, 43 and 51 kg/ha for nitrogen, phosphates and potassium compounds, respectively [341].

10.1. *Impacts of the Latin American soy boom*

Biomass production for bioenergy will increasingly take place in developing countries with favourable climatic conditions, surplus agricultural land and low labour costs. The long-term sustainability of such projects needs careful evaluation. Areas of concern comprise the socio-economic impacts in bioenergy producing countries, in particular those associated with the intensification of agriculture. The low rural population density in South America has long permitted highly inefficient land-use practices. Ideally, bioenergy should be produced on surplus agricultural land in order to avoid competition with food production. Socio-economic impacts may be severe in particular in case of large-scale, export-oriented bio-energy production. Agricultural intensification easily leads to negative social impacts as increased mechanisation is associated with decreased labour needs.

Notwithstanding the considerable negative impacts of large-scale adoption of soy monocultures, the global demand for this commodity is growing. Most of this demand growth will be met by South American producers. Soy planted area in South America is expected to increase from 38 Mha in 2003/2004 to 59 Mha in 2019/2020. Total production of Brazil, Argentina, Paraguay and Bolivia will rise 85% to 172 Mt or 57% of the world production. GMO-free soy is by far the most important export commodity of Bolivia. The Gran Chaco has a potential for irrigated agriculture similar to that of the United States great plains. While soybean farming in the tropical lowlands of Bolivia is profitable in the short-run, it may not be sustainable economically, socially and environmentally in the long-run [342]. Introduction of soybean in Bolivia has led to deforestation and to a shift of landownership to big farms owned by foreign investors [278].

On a business-as-usual basis, the currently perceived problems of mega-scale soybean production (Table 20) are expected to exacerbate. However, an alternative scenario – Integrated Crop Livestock Zero Tillage system – exists for substantial increase in

South American soybean production without conversion of valuable natural ecosystems [3]. Integration of (zero-tillage) crop (*i.e.* soy) cultivation with cattle raising can reach higher per hectare yields and stocking rates through better utilisation of soil and fodder resources, provided a means to prevent soil exhaustion for annual crops, and can contribute to achieve the forecasted demand for soy of 300 Mt/yr by 2020 [3]. Most expansion of soy production is expected to take place on existing idle lands and pasture lands. Integrated soy-livestock adoption can accommodate nearly 12 million heads of cattle in Brazil and 10 million in Argentina. This would reduce pressure on Chaco, Cerrado and Amazon forest biomes. The integrated system brings substantial benefits: increased employment on area basis, increased land value, lower mechanisation and fuel costs and reduced agrochemicals costs. Requirements are development of more efficient and intensive yet ecologically sustainable forms of land use and monitoring and enforcement of environmental and spatial planning laws.

Deforestation continues to be a dominant land-use trend in South America. The expansion of soybean cultivation threatens ecosystems such as the Chaco bush savannah, Yungas subtropical forest, Cerrado savannah and Amazon rainforest [111]. The expansion of soy is damaging also indirectly as other environmentally harmful activities such as cattle ranching and logging are accelerated due to infrastructural projects developed specifically for soy [151]. Large-scale clearing associated with logging or conversion to plantations, pasture land and new settlements accounts for the majority of tropical deforestation [343,344]. Forest clearing is a big contributor to global warming, accounting for some 15% of annual GHG emissions [345]. Brazil's soybean area could potentially increase from 18.4 Mha in 2003 to 54 Mha (or even 118 Mha) in 2052 [156]. Realisation of the current short- to medium-term soy expansion plans of the four aforementioned Latin American producing countries would lead to much larger export values for soy than the forecast capacity of the world market causing oversupply, with worrying consequences.

In Paraguay (with soybean production forecast 2012/2013 of 7.8 Mt) there is no compulsory government environmental requirement for the production of feedstocks or the industrial processing for biofuels. There are no criteria established for GHG emissions, land-use change or biodiversity issues. Certification is only becoming an issue for certain export markets.

As soy biodiesel developed in Argentina and Brazil only as from about 2004, this biofuel cannot be held responsible for the prior environmental effects of the rapidly expanding South American monoculture destined to the food and feed markets. However, it cannot be denied that currently soy biodiesel is contributing to the potential land use connotations and has both social and environmental implications which should be taken seriously. The South American soybean chain needs to evaluate the environmental performances of its products (soybeans and derivative meal and oil, and soy biodiesel) and improve the sustainability – currently seriously compromised. Unsustainable exploitation of natural resources should be halted.

10.1.1. *Sustainability of Brazilian soy biodiesel*

In the past, discussion on sustainability of biomass/bioenergy in Brazil has focused more on social and biodiversity issues than on GHG effects (as in EU). However, the recent Low Carbon Agriculture (ABC) program (2010) indicates that Brazil is now taking climate change mitigation more seriously [189]. Yet, data for GHG calculations are still mostly lacking. Indirect effects of soybean production on GHG emissions and other sustainability criteria are more important than the direct effects.

Brazilian soy biodiesel produces a high pressure on the environment [104]. Elbersen et al. [346] have assessed the sustainability of Brazilian soybean cultivation for biodiesel at the specific conditions of the Cerrado biome as the largest proportion of the expansion of soybean acreage occurs in the Cerrado region. The rather acid soils of the Cerrado require heavy doses of lime (700–3200 kg/ha) to be applied, which determine high energy costs for mining, processing, transportation and distribution [347]. Pimentel et al. [33] have (erroneously) claimed a negative energy balance for soy biodiesel in US conditions assuming such heavy lime use (4800 kg/ha). Cerrado soils also need that minimum amounts of 30 kg P_2O_5 and 60 kg K_2O are applied per hectare requiring energy equivalent to some 0.32 and 0.38 kg CO_2/kg, respectively. The phosphorus application rate in the Cerrado is twice as high as in Southern Brazil. Little irrigation is used. The total energy input required for Cerrado soybean cultivation amounts to 50–100 kg C/ha. The largest uncertainty as to C losses regards changes in soil organic matter (SOM). In the long run, continuous cultivation of soybean is detrimental to soil quality and rotation of soybean with other crops is to be preferred.

The net carbon balance in soybean cultivation ranges from losses of 700 kg C/ha under poor management conditions (primarily due to SOM loss) to ‘savings’ of 300 kg C/ha under proper management in rotational systems. Assigning the gains or losses of GHG emissions to soybean oil requires proper allocation in LCAs. In first approximation it appears that Cerrado soybean for biodiesel may not contribute significantly to save GHG emissions. Moreover, due to the expansion of the land area for the cultivation of soybeans, *i.e.* conversion of natural lands to grassland and then to arable land, changes in above- and below-ground carbon stock should be accounted for in estimating the contribution that Cerrado soy biodiesel could make to global GHG emission savings. Above-ground biomass of Cerrado vegetation ranges from 20 to 80 t C/ha with approximately twice as much organic matter below ground. Total CO_2 losses due to (indirect) clearing of Cerrado lands were estimated to range from 30 to 140 t C/ha [346]. Total losses of carbon and other GHGs might therefore easily exceed potential savings manifold. Recovering the initial losses could take several decades to over a hundred years. Similar conclusions were drawn by others [106,270,288]. Values of the same magnitude apply for the Argentine Chaco biome. The Cramer Commission criteria have mentioned a maximum acceptable payback time of 10 years [239].

Due to the development of agricultural production in the Cerrado also the water quality, water discharge and soil erosion sediment load have changed considerably. Brazil loses a great amount of nutrients and emergy by producing soybean and soy products for export [103]. Sustainable land use requires mitigation of these impacts even though it is not possible to prevent eutrophication and erosion completely. In the present scenario, GHG demands, loss of biodiversity and efficient use of water do not meet the sustainability requirements. A more sustainable soybean biodiesel production chain is needed in Brazil.

10.1.2. *Sustainability of Argentinean soy biodiesel*

In Argentina environmental policy and enforcement are in short supply. The Argentinean government, happy with the economic profits deriving from the present status quo, is not actively promoting change in the agricultural sector. However, it is a very sensitive issue which is being addressed for the export market. Initiatives have been launched towards an integral production system labelled “Environmental Agricultural Certification using No Till Conservation” aiming at differentiating production and a certified and sustainable agribusiness and biofuels industry in Argentina [348]. Sustainability standards for biofuels are under development and certification initiatives are being set up to ensure environmental standards including minimisation of agrochemicals (pesticides) use.

There are no specific official environmental or social sustainability criteria for biofuels in Argentina. In particular, there are no GHG sustainability requirements for the domestic market. However, the government clearly monitors criteria and regulations in export countries in order to avoid restrictions. As to the USA, in mid-2009, Argentina has presented comments to EPA's Regulation of Fuels and Fuel Additives, and the change to the U.S. Renewable Fuel Standards. It showed that Argentine soy biodiesel reduced GHG emissions far more than the established 22%. EPA's rulemaking currently establishes that soy-based biodiesel meets the 50% reduction in GHG emissions required to qualify for the biomass-based diesel category (*cf.* Ref [349]). Argentina has also challenged EU's recent CCP which establishes that biodiesel from soybean oil does not meet the minimum GHG emissions saving level. Various estimates of GHG savings of typical Argentine biodiesel *vs.* fossil diesel have been reported: 30.8% (EU-RED Annex V), 51% (JRC), 56% (ISCC) and 57% (E4Tech). INTA has reported energy use and GHG emissions for soy biodiesel from feedstock produced on prior agricultural land using no-tillage practice [349]. Since 90% of soybean is originating from already agricultural land LUC was not considered. Industrial conversion (crushing, refining and transesterification) was modelled according to European values even though Argentine facilities (including ports) are more modern with better overall efficiencies due to scale. Soy biodiesel produced with high fertiliser input leads to reduction in energy and GHG emissions compared to the reference diesel of 67.2% and 73.6%, respectively. The GHG reduction meets EU-RED requirements [12]. Compliance with the land of origin of sustainable soybean has been proved by INTA's Maps Methodology (based on satellite images, soil charts, administrative land registers and site surveys), showing approved 'GO' areas. CARBIO operates a voluntary certification scheme (CSCS) – not (yet) recognised by EU – for Argentinean soy [316].

The Round Table on Responsible Soy (RTRS) is an international multi-stakeholder initiative on voluntary basis specifically for soybean producers, processors, traders, financial institutions and non-governmental organisations created in 2004 with Excecutive Secretariat in Buenos Aires aiming at promoting economically viable, socially equitable and environmentally responsible soy production [350]. RTRS also acts as an international forum for discussion on sustainable soybean production practices. Although RTRS (founding organising committee: Grupo Maggi, Cordaid, Coop, WWF, Fetraf-Sul, Unilever) is a global platform of stakeholders in the soy value chain (supply, demand and civil society) the initiative is dominated by industry. Total membership amounted to 150 in April 2012. In June 2010 RTRS has finalised a set of auditable principles and criteria for use with a certification scheme (International RTRS Standard Version 1.0) and appropriate monitoring and verification mechanisms to reinforce these standards [350]. The RTRS certification process issues compliance certificates valid for 5 years, first assigned to South American soy producers in June 2011. The RTRS production standard is based on five principles: (i) legal compliance and good business practice; (ii) fair labour conditions; (iii) responsible community relations; (iv) environmental responsibility; and (v) good agricultural practices. Each principle consists of criteria with auditable short- and medium-term indicators. The 'Basel Criteria for Responsible Soy Production' [247] have been used as a background document. The RTRS standard includes Integrated Crop Management (ICM) measures and practices in soy production as well a GHG calculator. The approach of RTRS towards ICM is based on prevention, technical measures for cultivation, early warning system, chemical and non-chemical crop protection, and emission reduction. The RTRS supply chain traceability system is based on a stepwise approach: (i) a system of trading certificates; (ii) mass balance (EU-RED compliant); and (iii) segregation and full traceability through the whole supply chain. Certified soy is separated from non-certified products.

The standard identifies those social, environmental and agricultural aspects of the operation (on- and off-farm) where improvement is desirable, *e.g.* conflicting land uses, health and safety, vegetation clearance, GAP, air, water and soil pollution, GHG emissions, soil quality (SOC), use of hazardous agrochemicals (in particular Endosulfan, Paraquat and Carbofuran), aerial spraying of pesticides (drift), *etc*. As soybean producers are using more pesticides every year, there is an implemented plan that contains targets for reduction of potentially harmful phytosanitary products. Techniques to maintain soil quality may include conservation agriculture, crop rotation, and balanced fertilisation. No-till farming and maintenance of permanent soil cover are techniques to control soil erosion.

RTRS criteria help soy farmers in Latin America to become legally compliant and get access to financial services. Mainstreaming RTRS compliance supports governments in their attempts to stop deforestation. RTRS for responsible soy production includes requirements for the preservation of areas with high conservation value, the definition and promotion of best management practices, and the respect for land tenure claims [351]. National interpretations of the RTRS generic standard will define applicable local indicators, guidelines or procedures for economic, social, and environmental aspects adapted to the local circumstances. Tomei et al. [213] have expressed scepticism of the likely effectiveness of biodiesel sustainability certification as applied to Argentinean soy and require a more precautious approach to ensuring that European demand incentivises only environmentally and socially positive biofuel production. They propose a chain of custody that physically separates certified feedstock, rather than providing it as an agricultural commodity. This has now been taken care of by the RTRS supply chain traceability system.

Sustainability is a fundamental objective in the development of the biodiesel industry. As a soy biodiesel producer Argentina is competitive in terms of a net positive energy balance [212,335,352], though below US level [127]. The GHG balance of Argentinean soy biodiesel is generally favourable, as compared to conventional diesel, but not when land-use change has incurred [105]. Making Argentinean soy biodiesel more environmentally competitive requires higher productivity, no deforestation, reduced tillage, application of soybean inoculation and crops succession, avoiding high toxicity pesticides and using biomass-based methanol for transesterification [105]. Argentina must also establish clear and uniform biofuels quality standards, improve its legal and regulatory framework, and conform to European sustainability requirements [353]. At present, the social sustainability of Argentinean biodiesel, dominated by a few players, is questionable (Table 1). A more equal distribution of benefits throughout society requires participation of SMEs in the emerging market [214].

Argentinean biodiesel producers need to enhance the environmental performance of their products in order to comply with international sustainability criteria [12,238,239]. Sustainable Argentinean biodiesel also requires diversification of feedstock crops and domestic use of biodiesel [214]. The Argentinean biodiesel feedstock is not entirely suitable (low oilseed yields per area) and requires more diversification. Diversification reduces the environmental impact from soy cropping, relieves the dependency of farmers and the whole biodiesel branch from just one feedstock and makes use of more efficient and productive biodiesel crops. Proposals for improvement of sustainability include replacement of fossil fuels in the production process by biodiesel, and use of sunflower oil and recycled raw materials (used vegetable oil).

New technology and management techniques not only helped spread soybeans into frontiers areas where it was not previously

planted, but resulted also in the intensification of land use in the Pampas. Frontier expansion and cropping intensification have led to worrying environmental and social consequences. Argentina's excessive reliance on a single agricultural technology is not environmentally sustainable. Intensified cultivation of soils includes the practice of direct sowing and use of GM soybeans, and requires a manifold increase in the use of pesticides (*cf.* Table 29) [44,141], reduced harvesting cycles allowing earlier spring harvest, and deforestation. Practices such as soil analysis and pest monitoring are low in Argentina. In order to overcome the biological and ecological problems in the soybean sector Argentina needs diversification of cropping patterns and tillage and planting systems and reduced reliance on glyphosate.

Soybean expansion in Argentina has an enormous impact on the environment and on people (*cf.* Table 1). Deforestation has proceeded at an exceptionally high rate: in the north of Argentina three to six times higher than world average [354]. Between 1972 and 2001 about 20% of the semi-arid Chaco, one of the largest forested biomes of South America, was deforested for soybean cultivation [201]. Most of the accelerating deforestation (782 kha between 1998 and 2002; 1109 kha between 2003 and 2007) occurred in North and Northeastern Argentina by advance of agriculture, especially soybeans. Forests and bushes have been cleared either mechanically, by fire or by application of herbicides. Although growing concern about the loss of Argentina's native forests has led to the ratification of the Forest Law 26.331 (Ley de Bosques, 26 December 2007) [355], its effectiveness in halting illegal clearing processes needs to be seen [213]. According to Greenpeace, the agricultural frontier expansion on the forested areas of Argentina for increased soy biodiesel production for export is no less than an environmental catastrophe [356]. Soybean expansion has also resulted in the conversion of ecosystems rich in biodiversity. More than 40% of the increased soybean area in Argentina has come from virgin lands, including savannahs and forests, thus causing a loss in biodiversity [93,199]. The environmental impacts of soybean production have repeatedly been addressed [3,93,153,200,356].

In the absence of a national agrarian policy in Argentina market forces have determined the direction of agricultural development, namely prioritisation of short-term economic profits over environmentally sustainable development. The Argentine agricultural sector overexploits its natural resources. The expansion has particularly severe impacts on the ecological integrity of marginal areas. However, even soybean intensification in the Pampas generates concern about nutrient depletion and pest buildup [14]. The economic success of Argentinean agriculture has taken place at the expense of its soil quality [357]. Not unlike the USA and Brazil, Argentina is a net nutrient discharger. Table 28 shows the NPK deficiency in Argentine crop production. With the low mineral fertiliser consumption in Argentina nutrient inputs are completely inadequate. Soil phosphorus and potassium contents have decreased. Nitrogen is largely restored by biological fixation. However, inadequate levels of available potassium reduce capacity of the plant to exploit nitrogen. A growing percentage of soils in Argentina is showing impaired nitrogen fixation. Soil N levels decline. The depletion by nutrient export leaves an unaccounted for ecological debt [200,358]. Nutrient loss in 2003 alone due to the continuous production of soy has been estimated in 1 Mt N and 227 kt P. These losses are not reflected in the market price of soybean [103]. In the past, the nutrient budget had been equilibrated by rotation of soybeans with crops (wheat, sunflower) and cattle. In the long term, draining of wetlands and clearing of forests and savannahs for monoculture soy cultivation invariably lead to soil erosion, lower yields and poor economic returns.

Table 29
Adoption of herbicide-tolerant soybeans and glyphosate rates of application in Argentina and the United States.[a]

Tillage practice	Soybean (Mha)	Percent RR soybeans	Rate of glyphosate application (kg/ha)
Conventional			
Argentina	3.1	75	1.10
USA	19.7	52	0.67
No-till			
Argentina	7.2	96	1.20
USA	9.7	64	0.78

After Ref. [336].

[a] Crop year 2000 estimates.

At the same time, there is also evidence of nutritional quality problems. Compared to soybeans and soybean meal from USA, Brazil, China and India, Argentinean soy products contain the lowest level of crude protein (32.6% on dry matter basis) compared to Brazil (39.3%), USA (37.1%) and China (44.9%). It has been suggested that the differences in protein levels observed stand in relation to the genetic modification to render soybean plants RR [54].

Technological progress has allowed some improvements in environmental impact:

- application technologies (Good Agricultural Practice),
- direct seeding technology,
- precision agriculture,
- increased yield (less land-use needs),
- reduction in toxicity of agrochemicals.

The future sustainability of Argentinean agriculture is not assured [200]. Argentina needs to transit from an intensification of soy agriculture to a sustainable intensification of soy agriculture. While INTA can claim a number of important successes related to the introduction of zero-tillage and biotechnology, and the improvement of management practices by small farmers, other challenges lie ahead: environmental sustainability, soil management, bioenergy, quality systems. Sustainable production of soy is possible dependent on the farming system. The Argentinean Association of Soil Science recommends management practices that include suitable crop rotations, conservation tillage, and the use of fertilisers [359]. Local agroenvironmental characteristics should be taken into account by means of appropriate conservational measures. The production of soy areas with fragile soils carries a greater risk of soil erosion and deterioration. Sustainable long-term agribusiness in Argentina needs elimination of land clearance and deforestation practices (with tight controls), avoidance of soil erosion and reduced use of agrochemicals (causing pesticide poisoning and pollution) [329]. Active conservation policies should be introduced. Public awareness and concern for the environment is generally low in Argentina. There is little information available about the ecosystem impacts of agrochemicals in Argentina [357].

Agricultural intensification and bio-energy (soy biodiesel) production in Argentina have numerous (in)direct socio-economic impacts (Table 1). The agricultural intensification impacts in Argentina are negative [198,200]. Soya produced on a mass scale in the soya republic of Argentina, where it is not part of the food culture but simply an export commodity, has upset the social, cultural, ecological, political and economic balance. Both forests and human rights have been swept aside. The unsustainable pace of expansion of soybean production in Argentina has caused a multitude of problems even well before the advent of the Argentinean soy biodiesel industry (which therefore cannot directly be blamed). The machinery-intensive production system ("farming without farmers") contributes to many social problems.

Agricultural growth in Argentina has not led to significant employment generation due to its relatively high capital intensive and land extensive nature. In the 2007 harvest, 60% of soy was produced by only 4% of the farmers. Mechanised plantations may employ as few as 1 person per 200 ha. Tenant farming has increased. However, as the soybean frontier has advanced primarily onto natural ecosystems in areas of low population density, local social threats are somehow limited.

At the turn of last century mega-expansion of soybean production with crop displacement had even impaired local and national food security and determined a massive lack of access to food. Land competition for food with soy could again become an issue in rural parts of northern Argentina. Paradoxally, Argentina has increased its production of animal feed for livestock (soymeal) abroad and fuelstock (soy oil). The growth of the soybean industry has triggered also other social problems. Critical points are the distribution of land and benefits from soy cultivation. Agricultural growth should be more equitable. The Argentinean agricultural sector is not socially sustainable. The distortionary tax system could well be at the origin of many social problems rather than soy cultivation itself.

A revision of the environmental and social impact of soybean cropping in Argentina is urgently needed. Argentina's soybean sector is further characterised by under-investment in agricultural research, and requires enforcement of phytosanitary protection norms. Government expenditure in agriculture in Argentina is extremely low, much smaller than in Brazil.

11. Biofuel sustainability in Europe

Biomass for energy conversion has traditionally been considered as a local resource. The present global demand for bioenergy can only be satisfied through an increase in access of biomass over a larger geographical area. This implies transportation and an increased level of emissions and net energy input which both reduce the benefits from bioenergy. International bioenergy trade is possible against a modest energy loss [360] but at the cost of considerable extra GHG emissions [262]. It has been reported that the net energy input typically amounts to 7–9% of delivered energy from the system for ship transportation of biomass within Europe over 1200 km; emissions over such transportation distances were deemed of minor importance relative to those from bioenergy systems in a local market [360]. Although transport of foreign (US, Brazil) biofuels into Switzerland was also considered to be of secondary importance only [361], intercontinental transport accounts for 8.9 g CO_2 eq/MJ (or 21% of total GHG) for US-EU and for 13.0 g CO_2 eq/MJ for Brazil-EU [128].

Estimated biofuel demand in EU under 5.75% (2010) and 10% (2020) biofuel replacement targets are 19.0 and 36.2 Mtoe, respectively. The European Commission expects that 70% of the biofuel feedstock will be produced domestically and 30% imported. The additional demand would lead to 4.7–7.9 Mha of ILUC and between 31 and 65 Mt CO_2 emissions annually, or a 81–167% increase in GHG emissions relative to the fossil diesel baseline [362]. The EU-27 is the world's second largest soybean importer (12.2 Mt in 2010/2011), mainly from Brazil, Paraguay, and the United States. Domestic production of soybeans is limited (1.16 Mt in 2011/2012). EU-27 crushes nearly 90% of its total soybean supply. Soybean meal is used as feed in the EU-27 livestock sector and competes with other oilseed meals for this use. Europe and other soybean-importing regions have established labelling laws for GM foods and require GM-free agricultural export. GM soybeans or oil produced from GM soybeans are not generally used for human food applications in the EU-27 owing to the negative perceptions of many EU consumers for GM food products. Because of the zero tolerance policy for unauthorised biotech European importers are generally resistant to purchase US soybeans [363]. As 93% of US soybeans are biotech, food companies have reformulated their products to avoid using US soybean oil. Most of the oil from processing GM soybean in the EU is used in biodiesel production.

It is the policy of the European Union to encourage production and use of more energy from renewable sources. Currently, the EU has set itself an objective to achieve a minimum share of 10% renewable energy in transport by 2020 [12]. This 10% share (by energy) in the EU market represents a strong export opportunity for rape, soy and palm oil producing countries. Where biofuels are used to achieve this target, these must meet a set of sustainability requirements (partly to be developed). For biofuels, corresponding criteria are set out in EU-FQD [259], *cf.* Section 9.2.1. They apply to biofuels/bioliquids produced in the EU as well as to imported products. The criteria apply since December 2010. In practice, biofuels made of crops that have been grown on land that used to be rainforest or natural grassland with a unique ecosystem cannot be considered as sustainable. Changes in the carbon stock of land resulting from indirect changes in land use and other sustainability aspects, such as competition with food, environmental effects, impacts on economic development, social welfare, *etc*., have not explicitly been considered.

There is growing interest within Europe for certified sustainable biomass. Soybeans from all sources that are used as feedstocks in the EU biodiesel industry may not qualify in the future for EU tax credits and use mandates because of requirements of EU-RED. Sustainability certification is necessary to ensure access to EU markets. The EU-RED sustainability scheme contains two options designed to reduce the administrative burden to economic commercial actors:

- use of recognised "voluntary schemes" (*cf.* Table 25) or "bilateral and multinational agreements" to show compliance with some or all of the sustainability criteria; and
- use of "default values" laid down in EU-RED to show compliance with the sustainability criteria or GHG emissions savings.

The EU default value for GHG savings for soy biodiesel (31%) disqualifies soy from tax benefits when used as a feedstock in the EU-27 biodiesel industry unless further action is taken. Partially as a result of RED implementation, US soybean exports to the EU fell by 41% in 2011 from 2010 levels.

Currently, the European Union is revising its policy options for the biofuels sector with a shift in focus from biofuel production to sustainable crop production [217]. Recently, formulated proposals for amending both EU Directives address:

- restructuring of the 10% road transport target by restricting the contribution of conventional biofuels (obtained from food crops) to their share ($<5\%$) in the consumption level for 2011;
- anticipation of the minimum required GHG emission savings threshold of 60% for new installations (effective as from 1st July 2014 instead of 2018); existing installations shall achieve GHG savings of at least 35% until 31 December 2017 and 50% as from 1 January 2018;
- explicit inclusion of land use (as crop production) in the calculation of GHG emission savings;
- simplification of calculation of GHG savings;
- introduction of crop-specific ILUC factors (55 g CO_2 eq/MJ for oilcrops);
- equal treatment for producers regardless of the location of production; and
- ending of subsidies for cultivation of biocrops by 2020.

The European Union has set the highest sustainability criteria in the world, which would ensure imports of only certified sustainable products.

Several aspects not detailed by sustainability criteria in the EU-RED (such as environmental or social issues) should be covered by other certification systems and bilateral agreements. In this regard various third party initiatives have been developed [309,364], *cf.* Section 9.4. The EC strategy expresses in particular concerns about the environmental impact of the current expansion of soy and palm oil in producer countries and calls attention for a need for integrated management of land, water and natural resources that promotes conservation and sustainable use including water and soil qualities and consideration for livelihoods and rural development [12,365]. Certification schemes with independent verification and audits can play a role in this process but are not seen as the only safeguard for sustainable bioenergy, *cf.* Sections 9.4 and 10.1.2. Unless such schemes are adopted worldwide, sustainable exports to EU could still simply be replaced by unsustainable production for other export markets.

12. Conclusions

Bioenergy production is not sustainable by definition. Biodiesel is a significant energy resource that provides part of the solution for complying with the worldwide pressure to diversify fuel sources, increase energy efficiency and sustainability and prevent and reduce pollution. Biodiesel is important for local and regional security of supply giving it a direct advantage over fossil fuel. The main drivers for bioenergy production in the EU and USA are sustainability and security of energy supply. In Brazil the focus is much more on socio-economic issues (more recently also on climate mitigation), in Argentina on trade balance. Soybean is a major oilcrop for biodiesel production (at least until 2020). Only demonstrably sustainable feedstock should be used. All agricultural production (not only for biodiesel) requires sustainability standards. The sustainability of increasing biodiesel use is not without controversy. The EU-RED biofuel demand targets are higher than the potential sustainable supply. Scaling up of the biodiesel feedstock production to meet at least 5% of EU demand for transportation fuels already places (partly) unsustainable demands on land, energy, water and nutrients (fertilisers).

Some major concerns on the impact of soybean cultivation and trade are as follows:

- Soybeans can be produced in an unsustainable way: for instance inducing natural forest clearing (Brazil, Argentina, Bolivia) [262,278], use of agricultural production methods with negative environmental impacts (Dust Bowl and eutrophication in USA, nutrient debt in Argentina, Brazil and USA, soil erosion in Argentina), production (often for export) with a high input of fertilisers and/or agrochemicals (China, Brazil, Argentina), or excessive energy consumption (China).
- Land use with negative leakage effects (spill-over) outside the area where the activity takes place (Gulf of Mexico *vs.* US Corn Belt).
- ‘Unsustainable’ soybean entering the trade chain, *i.e.* segregation of certified and non-certified products. Audited soybean needs to be traceable from production to end use.
- Negative economic and social effects in soybean exporting regions: unequally shared benefits of soybean production between stakeholders such as farmers, consumers and traders (Argentina, Bolivia).
- Replacement of the regional production of food crops by energy crops for export (Argentina).
- Regional water scarcity due to increased production of bioenergy crops by withdrawal of water for irrigation or increasing evapotranspiration on land use [234].
- Loss of biodiversity due to expanded monocultures and deforestation (Argentina, Brazil).
- Health hazards due to pesticides use (Argentina, Brazil).

Table 30 illustrates problems with sustainability of soybean cultivation and soy biodiesel production in the main producing countries. Soy is not an efficient and sustainable option for large-scale production of biodiesel [214,282].

The environmental and social problems related to the current South American soybean production models have not got unobserved: decrease in soil fertility, intoxication of people and wildlife by agrochemicals, expulsion of small farmers from their lands, forest destruction for new crop areas, soil and water contamination, soil loss by erosion, biodiversity losses and contributions to global warming. In Argentina, production of a single commodity for the world market has even taken priority over concerns for national food security. The dominant factors determining the environmental and biodiversity impacts of biofuels are the types of lands used for producing biofuel feedstock (forestland, cropland, marginal or degraded lands) and the feedstock production practices employed, including the plant species [349]. Monoculture is neither good for soils nor for biodiversity. Farmers should be encouraged to return to the more sustainable crop rotation model. Monoculture also carries high susceptibility to catastrophic failure and has impact on wildlife and landscape.

Major environmental concerns for Brazilian soy are net-carbon results, biodiversity conservation, and required inputs. The biodiversity of the Cerrado is high and important for the South American continent. Argentina is the world's most efficient soy producer but not the most sustainable. Soyarisation of the Argentine economy is based on vulnerable and unsustainable farming. Argentina has adopted GM technology more rapidly and more radically than any other country without taking proper safeguards to manage resistance and protect its soil fertility. Argentina is becoming increasingly conscious of the need for changes in its farming practices. The combination of no-till with soya monoculture is not a sustainable alternative to crop rotation farming.

Compared with the fossil reference, the Argentinean pathway to biodiesel (including deforestation) has a worse performance in all the impact categories with the exception of energy consumption. Significant influences in the environmental impact are land-use changes, BNF and use of fertilisers and pesticides, the soybean production method, use of alcohol, and the transport system.

Table 30
Sustainability of soy biodiesel of main producers.[a]

Sustainability criterion	USA	Brazil	Argentina	China
Environmental	±	±	–	–
Energy consumption	+	±	+	–
GHG emissions	+	–	±	–
Nutrient depletion	±	±	–	+
Soil erosion	+	±	–	
Pollution	–	–		–
Agrochemicals	+	–	–	–
Deforestation	+	–	–	
Biodiversity		±	–	
Social	+	±	–	
Health	+	–	–	
Inequality	+	±	–	
Human rights	+	±	–	
Economic	±	±	+	–

[a] Positive score (+); negative score (–).

Already by 2001, RR soya growers in Argentina were using more than twice as much herbicide as conventional soya farmers, largely because of unexpected problems with tolerant weeds. Glyphosate use has continued to rise ever since. The excessive use of this herbicide has caused shifts in the composition of weed species, the emergence of resistant superweeds, and changes in soil microbiology. Similar problems are occurring to some extent in the US.

Expanding the system to account for crops succession will help to better model the system inputs in the agricultural phase. Although the position of Argentina as a soybean-based biodiesel exporter is cost-competitive it is not from the environmental point of view unless certain actions are undertaken: avoiding deforestation, applying reduced tillage and crops succession, applying soybean inoculation methods, increasing yield, using low-toxicity pesticides and using biomass-based alcohols in fatty acid ester production. The improvements are necessary to comply with international sustainability criteria for biofuels production. Further considerations should be made to account for indirect land-use changes attributable to soybean cultivation.

GHG mitigation in the transport sector depends on the feedstock used and requires that emissions from direct and indirect land-use changes are minimised. Global road transport is increasing steadily and consequently also GHG emissions. While biodiesel is but one of a limited range of current options to reduce road transport GHG emissions if produced sustainably, significant reductions also derive from less transport, more efficient vehicles and more efficient driving habits, low-carbon fuels and increasing use of public transport. Although voluntary biodiesel certification schemes, such as the Round Table on Responsible Soy (RTRS), are a positive development, their direct effectiveness remains unclear, even when globally adhered to. Indirect effects of biodiesel comprise the displacement of agricultural production onto uncultivated areas with impacts on biodiversity, GHG savings and local land rights, as well as raising food commodity prices. The expansion of soy production in South America has been described partly as a consequence of the diversion of soy production for corn in the US (to meet bioethanol targets). Increased demand and prices for oilseed rape for biodiesel in the EU have been linked to the expansion of palm oil production in South-East Asia. Displacement of agricultural activity is significant from a GHG perspective as many forms of land-use changes result in significant carbon release. Biodiesel requires an improved sustainability performance that includes managing indirect land use. A more sustainable soybean chain needs organic production models and other process integration technologies which decrease the dependence on external non-renewable resources by increasing internal recycling and decreasing the use of chemical inputs.

As soy biodiesel combines a relatively low potential for the reduction of GHG emissions with a low oil productivity (*i.e.* high land area requirement) and can contribute to food supply pressures, IEA expects that this product will be phased out by 2050 [282]. This could even be much earlier. A sustainable biodiesel market requires a diversification of feedstock crops (second-generation). A genuinely sustainable biodiesel industry should be possible but cannot be assured.

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